SoftwareX 23 (2023) 101451

Contents lists available at ScienceDirect

SoftwareX

journal homepage: www.elsevier.com/locate/softx

Original software publication

Pypiezo-GO: A software tool for processing electromechanical measurements of piezoelectric reduced graphene oxide-cement composites

Daniel A. Triana-Camacho [a,*], Jorge H. Quintero-Orozco [a], Enrique García-Macías [b]

[a] Ciencia de Materiales Biológicos y Semiconductores (CIMBIOS), Escuela de Física, Universidad Industrial de Santander, Cra 27 Calle 9, Bucaramanga, Colombia

[b] Department of Structural Mechanics and Hydraulic Engineering, University of Granada, Av. Fuentenueva sn, 18002 Granada, Spain

ARTICLE INFO

Article history:
Received 10 May 2023
Received in revised form 16 June 2023
Accepted 17 June 2023

Keywords:
Cyclic voltammetry
DataFrame
Open circuit potential
Piezoelectricity
Python language
Reduced graphene oxide

ABSTRACT

Self-diagnostic composites have become increasingly popular for structural health monitoring due to their ability to develop load-bearing strain sensors. Piezoelectric cement composites, in particular, represent an emerging area of research with vast potential for developing innovative self-powered or ultra-low power consumption sensors. In this context, this paper presents `Pypiezo-GO`, a software tool designed for the electromechanical characterization of reduced graphene oxide (rGO)-cement composites. The software tool, developed as an online cloud computing platform, accesses a database organized into DataFrame structures. The database contains the measurements from a set of experiments conducted on rGO-cement samples, including open circuit potential, cyclic voltammetry, and compressive testing. On this basis, `Pypiezo-GO` allows extracting the electrical properties of the samples, including their capacitance and piezoelectric factors. Furthermore, the platform enables the comparison of experimental time series with numerical predictions from a lumped circuit model implemented in MATLAB/Simulink, which is also included in this contribution. The presented software code is intended to represent a valuable tool for the development of new piezoelectric cement composites for strain self-sensing applications.

Code metadata

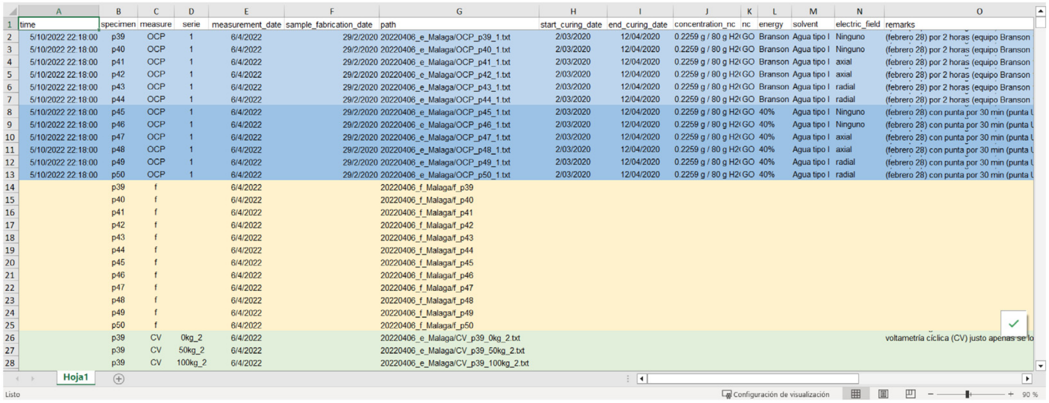
Current code version	v1.0
Permanent link to code/repository used for this code version	https://github.com/ElsevierSoftwareX/SOFTX-D-23-00305
Permanent link to reproducible capsule	N.A.
Legal Code License	GPL
Code versioning system used	git
Software code languages, tools, and services used	Python 3.7
Compilation requirements, operating environments & dependencies	The file Medidas_GO.xlsx and the path files of impedance, voltammetry, open circuit potential, and compressive measurements
If available Link to developer documentation/manual	https://github.com/dantrica/cement-based-composites/blob/main/README.md
Support email for questions	dantrica@saber.uis.edu.co

1. Motivation and significance

Carbon-based additives, such as carbon nanotubes (CNTs), graphite, carbon fillers (CF), graphene oxide (GO), or reduced graphene oxide (rGO), have been widely studied over the past decade to enhance the physicochemical properties of cementitious materials, such as stiffness, strength, or fracture toughness, and to improve hydration reactions and reduce carbonation contents [1–3]. More recently, researchers have found that these composites can also provide cement pastes with strain self-sensing capabilities, being possible to develop load-bearing sensors with high potential for structural health monitoring (SHM)

* Corresponding author.
E-mail addresses: dantrica@saber.uis.edu.co (Daniel A. Triana-Camacho), jhquinte@uis.edu.co (Jorge H. Quintero-Orozco), enriquegm@ugr.es (Enrique García-Macías).

https://doi.org/10.1016/j.softx.2023.101451



time	specimen	measure	serie	measurement_date	sample_fabrication_date	path	start_curing_date	end_curing_date	concentration_nc	nc	energy	solvent	electric_field	remarks
5/10/2022 22:18:00	p39	OCP	1	6/4/2022	29/2/2020	20220406_e_Malaga/OCP_p39_1.txt	2/03/2020	12/04/2020	0.2259 g / 80 g H2(	GO	Branson	Agua tipo I	Ninguno	(febrero 28) por 2 horas (equipo Branson
5/10/2022 22:18:00	p40	OCP	1	6/4/2022	29/2/2020	20220406_e_Malaga/OCP_p40_1.txt	2/03/2020	12/04/2020	0.2259 g / 80 g H2(	GO	Branson	Agua tipo I	Ninguno	(febrero 28) por 2 horas (equipo Branson
5/10/2022 22:18:00	p41	OCP	1	6/4/2022	29/2/2020	20220406_e_Malaga/OCP_p41_1.txt	2/03/2020	12/04/2020	0.2259 g / 80 g H2(	GO	Branson	Agua tipo I	axial	(febrero 28) por 2 horas (equipo Branson
5/10/2022 22:18:00	p42	OCP	1	6/4/2022	29/2/2020	20220406_e_Malaga/OCP_p42_1.txt	2/03/2020	12/04/2020	0.2259 g / 80 g H2(	GO	Branson	Agua tipo I	axial	(febrero 28) por 2 horas (equipo Branson
5/10/2022 22:18:00	p43	OCP	1	6/4/2022	29/2/2020	20220406_e_Malaga/OCP_p43_1.txt	2/03/2020	12/04/2020	0.2259 g / 80 g H2(	GO	Branson	Agua tipo I	radial	(febrero 28) por 2 horas (equipo Branson
5/10/2022 22:18:00	p44	OCP	1	6/4/2022	29/2/2020	20220406_e_Malaga/OCP_p44_1.txt	2/03/2020	12/04/2020	0.2259 g / 80 g H2(	GO	Branson	Agua tipo I	radial	(febrero 28) por 2 horas (equipo Branson
5/10/2022 22:18:00	p45	OCP	1	6/4/2022	29/2/2020	20220406_e_Malaga/OCP_p45_1.txt	2/03/2020	12/04/2020	0.2259 g / 80 g H2(	GO	40%	Agua tipo I	Ninguno	(febrero 28) con punta por 30 min (punta U
5/10/2022 22:18:00	p46	OCP	1	6/4/2022	29/2/2020	20220406_e_Malaga/OCP_p46_1.txt	2/03/2020	12/04/2020	0.2259 g / 80 g H2(	GO	40%	Agua tipo I	Ninguno	(febrero 28) con punta por 30 min (punta U
5/10/2022 22:18:00	p47	OCP	1	6/4/2022	29/2/2020	20220406_e_Malaga/OCP_p47_1.txt	2/03/2020	12/04/2020	0.2259 g / 80 g H2(	GO	40%	Agua tipo I	axial	(febrero 28) con punta por 30 min (punta U
5/10/2022 22:18:00	p48	OCP	1	6/4/2022	29/2/2020	20220406_e_Malaga/OCP_p48_1.txt	2/03/2020	12/04/2020	0.2259 g / 80 g H2(	GO	40%	Agua tipo I	axial	(febrero 28) con punta por 30 min (punta U
5/10/2022 22:18:00	p49	OCP	1	6/4/2022	29/2/2020	20220406_e_Malaga/OCP_p49_1.txt	2/03/2020	12/04/2020	0.2259 g / 80 g H2(	GO	40%	Agua tipo I	radial	(febrero 28) con punta por 30 min (punta U
5/10/2022 22:18:00	p50	OCP	1	6/4/2022	29/2/2020	20220406_e_Malaga/OCP_p50_1.txt	2/03/2020	12/04/2020	0.2259 g / 80 g H2(	GO	40%	Agua tipo I	radial	(febrero 28) con punta por 30 min (punta U
	p39	f		6/4/2022		20220406_f_Malaga/f_p39								
	p40	f		6/4/2022		20220406_f_Malaga/f_p40								
	p41	f		6/4/2022		20220406_f_Malaga/f_p41								
	p42	f		6/4/2022		20220406_f_Malaga/f_p42								
	p43	f		6/4/2022		20220406_f_Malaga/f_p43								
	p44	f		6/4/2022		20220406_f_Malaga/f_p44								
	p45	f		6/4/2022		20220406_f_Malaga/f_p45								
	p46	f		6/4/2022		20220406_f_Malaga/f_p46								
	p47	f		6/4/2022		20220406_f_Malaga/f_p47								
	p48	f		6/4/2022		20220406_f_Malaga/f_p48								
	p49	f		6/4/2022		20220406_f_Malaga/f_p49								
	p50	f		6/4/2022		20220406_f_Malaga/f_p50								
	p39	CV	0kg_2	6/4/2022		20220406_e_Malaga/CV_p39_0kg_2.txt								voltametría cíclica (CV) justo apenas se lo
	p39	CV	50kg_2	6/4/2022		20220406_e_Malaga/CV_p39_50kg_2.txt								
	p39	CV	100kg_2	6/4/2022		20220406_e_Malaga/CV_p39_100kg_2.txt								

Fig. 1. Excel spreadsheet that manages the measurements from the mechanic and electric tests.

applications [4]. Most studies have focused on their piezoresistive properties as the main strain self-sensing principle [5–7].

For instance, it is worth noting the work by Ding and co-authors [8] who reported the electromechanical characterization of CF-CNTs cement composites. By directly synthesizing 1.5 vol.% of CNTs on the CF, their results reported excellent increases in the mechanical properties as well as in the piezoresistive properties (0.506% MPa^{-1}/221.6). Nevertheless, while promising, piezoresistive sensors require an external electric power supply to conduct electrical resistivity measurements and to infer the strain condition, which represents a serious obstacle to their field implementation. Therefore, researchers are exploring emerging self-powered sensing technologies, such as piezoresistive materials combined with energy harvesting devices [9], piezothermal sensors [10], or piezoceramic composites [11]. In this light, Triana-Camacho et al. [12] reported the development of piezoelectric rGO-cement composites with self-powered strain sensing capabilities. These materials require a minimal power supply to record and transmit the electrical output data, making it possible to adopt ultra-low power consumption electronics for SHM field applications. The electromechanical characterization of these materials for strain sensing applications is challenging, since it involves a series of mechanical and electrical tests involving different measurement systems. This requires researchers to manually work on the data processing of the experimental data, with software tools such as Origin, Excel, or software available in potentiostats [13]. To facilitate this task, this manuscript presents a software tool called `Pypiezo-GO` for the processing of the electromechanical tests conducted for the rGO-cement samples reported in [12].

`Pypiezo-GO` comprises a sequence of methods developed in Python language and implemented on a Google Colaboratory notebook, which is suitable for efficient cloud computing and simplifies the cooperative work between the researchers. The experimental database is organized with a Data- Frame called `Medidas_GO.xlsx`. This Excel file includes the paths and metadata of the experimental measurement files with extensions `.txt` or `.xlsx`. In particular, the experimental database includes the measurement records extracted from cyclic voltammetry (CV), open circuit potential (OCP), and compressive testing (CT), as reported in Ref. [12]. On this basis, `Pypiezo -GO` synchronizes the mechanical and electrical records, calculates the effective capacitance and the piezoelectric parameters of voltage g_{33} and charge d_{33}, which represent the key features of these materials for their use as strain sensors. The code also includes the possibility of calibrating a lumped equivalent circuiy developed in MATLAB/Simulink for signal processing applications.

2. Software description

The experimental database is organized in the Excel file `Medidas_GO.xlsx`, which contains the directories of all the measurement files (CT, CV, and OCP), as well as the metadata about the fabrication methodology of the rGO-cement specimens (Fig. 1), such as the start and end dates of the curing, the filler concentration, the dispersion energy, and the solvent agent. This information is loaded in code cell 1.1. in `Pypiezo-GO` (see Fig. 2), where the user has to choose one or more specimens to perform the analysis. Then, the experimental data are loaded in code cells 1.2. and 1.3., which include the electrical (voltage and current) and mechanical (force and deformation) time series. Such data are then synchronized in the code cell 1.4. by linear time interpolation using the method `interpol`. Afterwards, the method `plot_electromechanical` in the code cell 1.5. is in charge of plotting the output graphs, and computing new electric (power, resistance, and fractional change in resistance (FCR)) and mechanic (strain and stress) data series. The code cells inside the module 2.0. contain the plotting options and the correlations between strain and other data series such as force, voltage, current, resistance, power, and FCR. Finally, the module 3.0. conducts the comparison between the numerical simulations of the equivalent lumped circuit described hereafter in Section 2.1 and the experimental curves in terms of FCR, electric power, and piezovoltage.

The module 4.0. (Analysis of voltammograms) allows getting the capacitance as a function of the applied force. To this aim, the capacitance of the samples is calculated by integrating the area under the CV curves for cyclical compression loads, including force values of 0, 500, 1000, 1500, 2000, and 2500 N. Note that, as indicated in Ref. [12], the integral of the voltammograms is related to the specimen's capacitance. The capacitance is a key magnitude to determine the piezoelectric charge parameter d_{33} together with estimating the correlation between the output piezovoltage and the applied force. Instead, the piezoelectric voltage parameter g_{33} depends only on the generated voltage, the applied force, and the geometry of the rGO-cement composites. Finally, the code cell 5.0. of `Pypiezo-GO` is dedicated to saving the electromechanical characterization parameters, the output plots, as well as their file paths into a new DataFrame saved with extension `.xlsx`.

2.1. Equivalent lumped circuit

An equivalent lumped circuit model implemented in MATLAB/Simulink environment to interpret and predict the experimental results is also included in `Pypiezo-GO`. For an in-depth discussion on the structure and accuracy of the equivalent circuit,

1.1. Selection of the specimen(s).

```
data = pd.read_excel('data/Medidas_GO_20220406.xlsx')
#path_list = data.path
#measure = ['OCP', 'f']

ss1 = input("Please select the specimens from (p39 - p50), for instance: p39 p44 ...] : ")

def to_list(string):
    li = list(string.split(" "))
    return li
picked_samples = to_list(ss1)

print('Chose specimen(s) is/are: ', picked_samples)
```

```
Please select the specimens from (p39 - p50), for instance: p39 p44 ...] : p39
Chose specimen(s) is/are:  ['p39']
```

Fig. 2. Code cell to support the selection of the specimen for analysis.

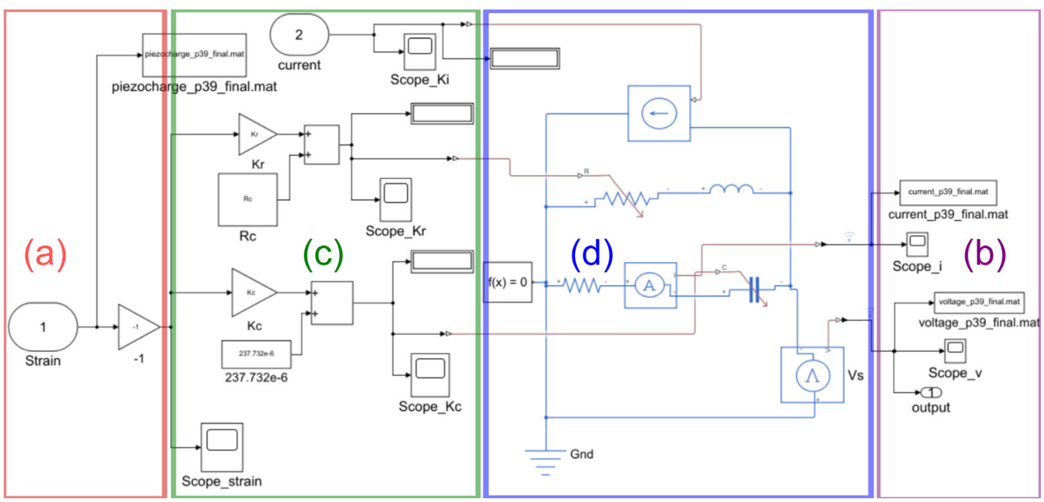


Fig. 3. Equivalent lumped circuit model implemented in Simulink. The model is organized into (a) input, (b) output, (c) electromechanical, and (d) circuit definition blocks.

readers may refer to the main work in [12]. The parameters of the circuit include the resistive λ_{R_m} and capacitive λ_{C_m} gauge factors, the cement matrix R_m and charge transfer R_{ct} electric resistances, as well as the inductance L and capacitance C_m of the composite. The Simulink model was designed with three major blocks: (i) inputs and outputs, which represent the applied strain on the rGO-cement composite as input, and the resulting electric current and voltage generated by the composite as outputs (see Figs. 3(a) and 3(b), respectively); (ii) electromechanical coupling blocks (Fig. 3(c)), which consist of transfer functions that establish the relationship between the parameters R_m and C_m and the applied strain; and (iii) the circuit model, composed of the piezoelectric (current source), piezocapacitive (charge transfer resistance and capacitance controlled by the applied mechanical strain), and piezoresistive branches (resonance inductor and resistance controlled by strain) (Fig. 3(d)).

The parameters of the model are estimated by inverse calibration using experimental data of generated voltage and mechanical strain. Specifically, the model calibration is defined as a minimization problem with a cost function involving the mean squared errors between the model predictions and the experimental data. The optimization problem is solved using the gradient descent optimization algorithm implemented in Simulink. To obtain physically meaningful solutions in the calibration, the model parameters are constrained to realistic intervals. In particular, the gauge factors λ_{R_m} and λ_{C_m} are restricted to the intervals $(0, \infty)$ and $(-\infty, 0)$, respectively. With regard to the intervals of the passive components, the resistances are restricted to ($\mathrm{R_m} > \mathrm{R_{ct}}$), while the capacitance ($\mathrm{C_m}$) and inductance (L) are forced to maintain positive values. In these analyses, given the suspicion about the applicability of linear piezoelectricity theory as reported in [12], the electrical current $i(t)$ is directly taken from the experimental data. Once calibrated, the simulation results are stored in the form of `.txt` files that are later processed in `Pypiezo-GO` for validation and comparison purposes.

2.2. Software architecture

`Pypiezo-GO` is not only a software that performs data processing of electromechanical testing data of piezoelectric cements; but it also represents a complete strategy to organize, analyze, process, and present dense databases in an efficient way as shown in Fig. 4.

To facilitate the use of `Pypiezo-GO` and share of sharing between users, Google Colaboratory was selected as the software framework because it offers an accessible environment that can interpret Python, HTML5, Markdown, and LaTeX codes, and all the computations are conducted entirely in the cloud

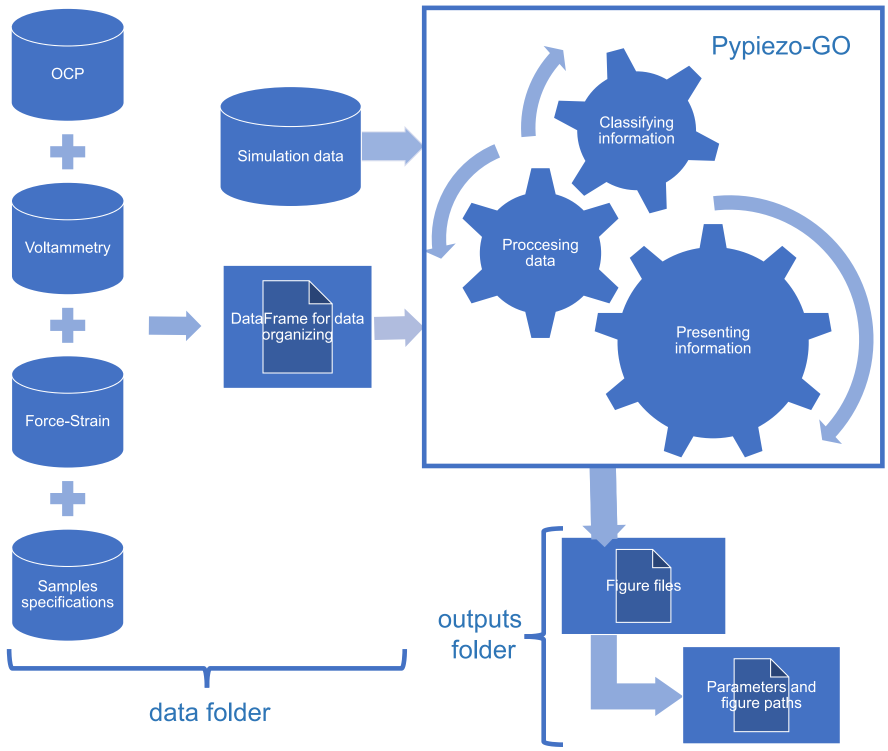


Fig. 4. `Pypiezo-GO` software architecture.

(Google Drive). To create a structure for manipulating the python scripts and the input and output data, three new folders called `scripts`, `data` and `outputs` are created inside the main folder. The `data` folder is intended to store the data from experiments organized into separate folders with names organized by the corresponding acquisition dates (year/month/day, for instance, 20190904). The `data` folder also contains the Excel sheet `Medidas_GO.xlsx`. Within these dated folders, the files are arranged with the measurement data denoted by: *measurement technique_sample name_measurement series*. For example, the first OCP measurement performed on the p49 sample has for name `OCP_p49_1`.

Once organized, the `Pypiezo-GO` script receives the information contained inside the DataFrame, and the data from the CS, CV, and OCP tests are classified according to the selected specimen(s) in separated DataFrames. Finally, the data series are processed to calculate the electromechanical characteristics of the samples. In this light, the tabular output data and graphs are respectively stored by means of DataFrames and figures in the `outputs` folder. Finally, the outputs of `Pypiezo-GO` in the shape of newly calculated data series, parameters are presented in graphical and tabular format in a log viewer, shown in Fig. 5.

2.3. Software functionalities

The primary functionalities of `Pypiezo-GO` (along with the Simulink model) are centered around the management, manipulation, modeling, and presentation of information from the electromechanical testing of piezoelectric cement composites, as elucidated in the following statements:

1. (`Pypiezo-GO`) Classify the information of the measurements (CT, OCP, CV) according to previously chosen specimen(s). It is essential to clarify that a specimen can be associated with different measurements or several series of the same test type.
2. (`Pypiezo-GO`) Synchronize data series from the mechanical (force) and electrical (voltage) experiments to obtain the piezoelectric voltage parameter g_{33}.
3. (`Pypiezo-GO`) Setting the combination options from data series of different measurements such as force, displacement, strain, voltage, and electric current or the new data series calculated by `Pypiezo-GO` as strain, electrical resistance, power, and FCR.
4. (`Pypiezo-GO`) Analyze the voltammograms at different constant compressive loads to determine the capacitance and the piezoelectric charge parameter d_{33}.
5. (Simulink model) Extract the parameters of the circuit model through the Parameter Estimator App. Subsequently, in `Pypiezo-GO`, the fitted outputs are compared with the experimental data series for validation and verification purposes.

3. Illustrative example

This section provides an illustrative example that shows the data manipulation and the result delivery using `Pypiezo-GO`. Specifically, this example demonstrates the determination of the piezoelectric properties of a rGO-cement specimen denoted as "p39". The process begins with the selection of the specimen(s), as illustrated in Fig. 2. Next, the code cell prompts the user to enter the sample's nomenclature. In this example, the specimen "p39" was entered. Afterwards, two new dictionaries (see code cells 1.2 and 1.3 of `Pypiezo-GO` in Figs. 6(a) and 6(b), respectively) are created to organize the data for the selected specimen. The second dictionary includes the mechanical and electrical data series.

In code cell 1.4., the method `interpol` allows the user to specify the time interval in the interpolation used for the time synchronization of the electromechanical records. It also provides a warning when the minimum and maximum times specified full outside that interval. Then, `plot_electromechanical` in code

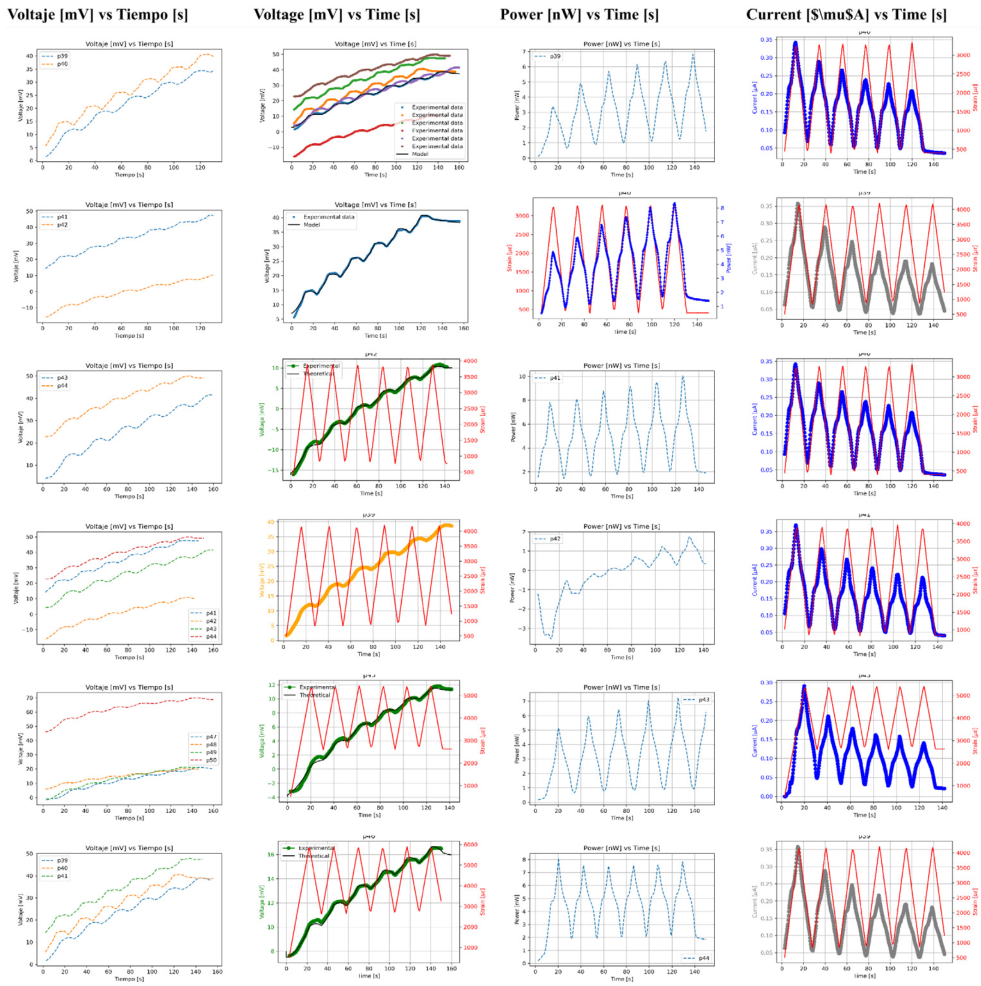


Fig. 5. Log viewer for presenting the new DataFrames created by `Pypiezo-GO`.

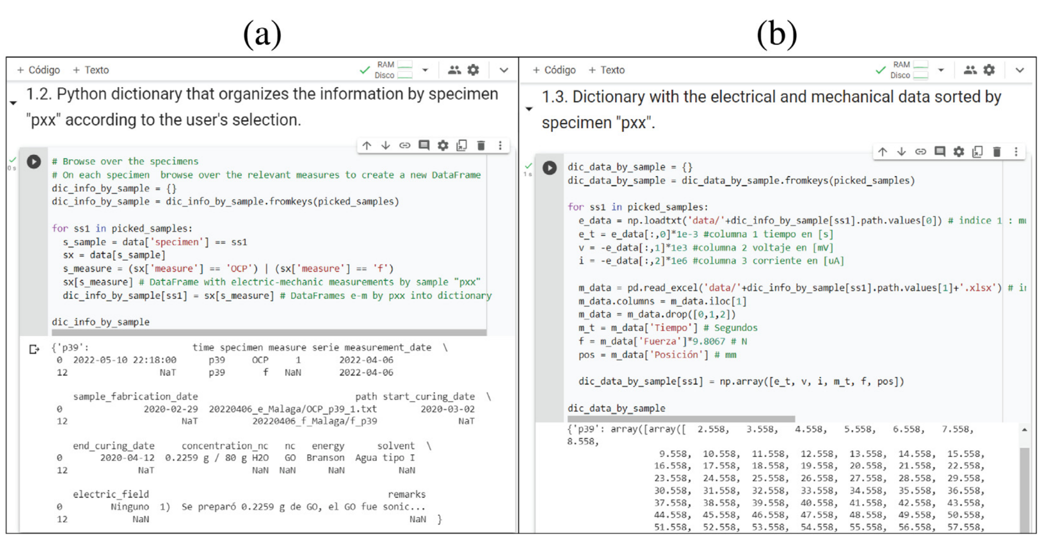


Fig. 6. Screenshots of cells 1.1. and 1.2. containing a programming structure based on dictionaries to organize the information by specimen according to the user's selection (a) and the dictionary with the electromechanical data (b).

cell 1.5. is responsible for configuring the plotting, labels, and analysis options shown in Fig. 7. The labels can be displayed in either Spanish or English.

Furthermore, in the code cell 2.1. Plotting options the previous methods are instanced to present the figures and results. In this example, the `interpol` method was called by typing the following arguments: `t_min_max = [2.56,13] and n=500`. In addition, the `plot_electromechanical` method was also instanced in the following code line: `option = 7, marker = '--', etiqueta = '', label_axes = 'en', dpi = 100`. This

```
'''
There are xx options (0 - XX) to choose the figure to be plotted,
according to set of specimens 'pxx'
option = 0 --- force vs time
option = 1 --- strain vs time
option = 2 --- force vs strain
option = 3 --- voltage vs time
option = 4 --- current vs time
option = 5 --- current vs voltage
option = 6 --- voltage vs strain
option = 7 --- voltage vs force
option = 8 --- current vs strain
option = 9 --- resistance vs strain
option = 10 --- resistance vs force
option = 11 --- potencia vs time
option = 12 --- resistance vs time
option = 13 --- Delta resistance / R vs strain
option = 14 --- Delta resistance / R vs time
option = 15 --- voltage / electrodes separation vs force / cross section
option = 16 --- nomalized strain vs time
option = 17 --- normalized current vs time
option = 18 --- power vs strain
'''
```

Fig. 7. Plotting options in Pypiezo-GO.

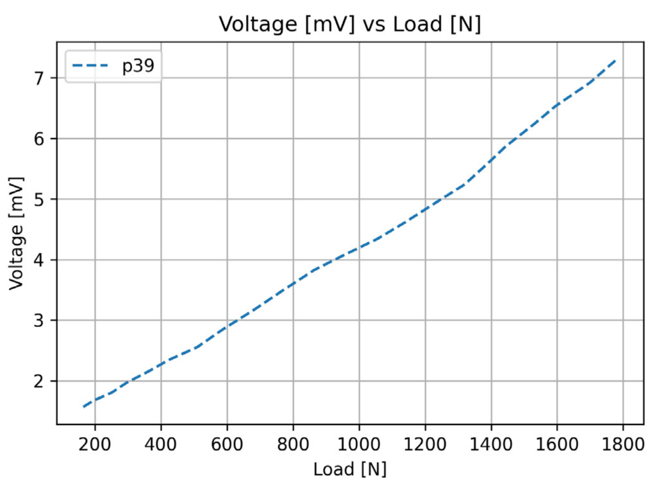


Fig. 8. Output voltage versus compressive load curve obtained for the specimen p39.

option is for constructing the voltage [mV] versus force [N] figure and calculating the piezoelectric parameter of voltage, which is presented in the output cell as g_33 = 12.19434782E-5 mVm/N. Additionally, Fig. 8 is generated to visually represent the results.

4. Impact

Piezoelectric cement composites have enormous potential for solving the scalability issues of self-diagnostic materials for SHM of civil engineering structures, which are typically located in remote sites without access to the electrical grid. For their application, it is essential to identify their strain sensing properties through specific electromechanical characterization tests [14–16]. Of particular interest are the piezoelectric voltage g_{33} and charge d_{33} coefficients, which are determined in this work through the combination of CT, OCP and CV following the methodology presented in [12]. To enable the processing of the measurement files and characterize the piezoelectric coefficients, this study was presented Pypiezo-GO, an open-source software program written in Python within the cloud platform Google Colab. Given the great potential of these composites, Pypiezo-GO is envisaged to represent a valuable tool for the scientific community working on piezoelectric composites for SHM applications. Specifically, the main impacts of Pypiezo-GO comprise:

- Enabling the analysis of large volume of data from electromechanical characterization campaigns with minimum computational time demands.
- Integrating the data obtained from different laboratory equipment.
- Representing a general methodology to organize the information from intensive experimental campaigns in a structured manner.

In addition, these impacts (i) can inspire future works investigating different types of nanomaterials to develop new smart cement composites, exploiting piezoelectricity as the main strain self-sensing principle and enabling the software tool (Pypiezo-GO) to analyze such properties. Besides, (ii) new experiments could be conducted to expand the presented database and so obtain a more representative characterization of the piezo properties of rGO-cement composites, including other volume fractions of rGO in the cement paste or inducing polarization during the curing stage. Finally, (iii) the presented lumped equivalent circuit can be enhanced to obtain more reliable predictions or it can be adapted to other smart composite materials. Increasing the size of the present database can be easily performed owing to the optimized architecture of the software, which allows organizing the data in an intuitive manner, even when different types of measurements have been carried out on each specimen. In addition, the user-friendly nature of Pypiezo-GO is enhanced by the popularity of organizing information in a dataframe structure, which is similar to popular software tools like Excel, Google Sheets, and Open Office calculus sheets. With Pypiezo-GO, users do not require licensed software such as Origin or Maple to process information or need to combine different software tools to achieve the same result.

5. Conclusions

Pypiezo-GO is a software tool designed to facilitate the organization, analysis, and processing of the measurements from experiments conducted using a Potentiostat/Galvanostat and a Universal Testing Machine for the electromechanical characterization of piezoelectric rGO-cement composites. The testing sequence include measurements of open circuit potential, cyclic voltammetry, and compressive tests, each of which comprises distinct data series, including time, voltage, current, force, displacement, among others. On this basis, `Pypiezo-GO` has been designed to integrate these data series in an intuitive manner and through cloud computing, enabling the estimation of the effective piezoelectric voltage g_{33} and charge d_{33} coefficients, which are fundamental for self-powered strain self-sensing applications. The presented open-source software also represents an ideal environment for constructing new equivalent circuit models for enhancing the understanding of rGO-cement composites, as well as to interpret experimental data and conduct signal processing applications.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request

Acknowledgments

The authors would like to acknowledge the financial support from the *ICETEX* through the funds program 890 of *MinCiencias* by the project numbers 82779 and 8286-3765, entitle *Piezoresistividad en Pasta de Cemento con Adición de Nanopartículas de Oro o Materiales Carbonosos*. Daniel A. Triana-Camacho want to give special thanks to scholarships program of *MinCiencias Programa de Becas de Excelencia Doctoral del Bicentenario - Corte 2, 2019*. And, E. García-Macías was supported by the Consejería de Transformación Económica, Conocimiento, Empresas *y* Universidades de la Junta de Andalucía (Spain) through the research project P18-RT-3128.

References

[1] Mendoza Reales OA, Arias Jaramillo YP, Ochoa Botero JC, Delgado CA, Quintero JH, Toledo Filho RD. Influence of MWCNT/surfactant dispersions on the rheology of Portland cement pastes. Cem Concr Res 2018;107:101–9. http://dx.doi.org/10.1016/j.cemconres.2018.02.020.

[2] Rodriguez B, Correa E, Arias Y, Quintero J, Calderón J, Mendoza O. Carbonation study in a cement matrix with carbon nanotubes. J Phys Conf Ser 2019;1247(1):012024. http://dx.doi.org/10.1088/1742-6596/1247/1/012024.

[3] Reales OAM, Jaramillo YPA, Ocampo C, Botero JCO, Quintero JH, Filho RDT. Anionic, cationic, and nonionic surfactants used as dispersing agents for carbon nanotubes and their effect on cement hydration. J Mater Civ Eng 2021;33(11):04021325. http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0003955.

[4] Dong W, Li W, Tao Z, Wang K. Piezoresistive properties of cement-based sensors: Review and perspective. Constr Build Mater 2019;203:146–63. http://dx.doi.org/10.1016/j.conbuildmat.2019.01.081.

[5] Qi G, Wang Q, Zhang R, Guo Z, Zhan D, Liu S. Effect of rGO/GNP on the electrical conductivity and piezoresistance of cement-based composite subjected to dynamic loading. Constr Build Mater 2023;368:130340. http://dx.doi.org/10.1016/j.conbuildmat.2023.130340.

[6] Tao J, Wang J, Zeng Q. A comparative study on the influences of CNT and GNP on the piezoresistivity of cement composites. Mater Lett 2020;259:126858. http://dx.doi.org/10.1016/j.matlet.2019.126858.

[7] Ding S, Xiang Y, Ni YQ, Thakur VK, Wang X, Han B, Ou J. In-situ synthesizing carbon nanotubes on cement to develop self-sensing cementitious composites for smart high-speed rail infrastructures. Nano Today 2022;43:101438. http://dx.doi.org/10.1016/j.nantod.2022.101438.

[8] Ding S, Wang X, Qiu L, Ni Y-Q, Dong X, Cui Y, et al. Self-sensing cementitious composites with hierarchical carbon fiber-carbon nanotube composite fillers for crack development monitoring of a Maglev girder. Small 2023;19(9):2206258. http://dx.doi.org/10.1002/smll.202206258.

[9] Birgin HB, García-Macías E, D'Alessandro A, Ubertini F. Self-powered weigh-in-motion system combining vibration energy harvesting and self-sensing composite pavements. Constr Build Mater 2023;369:130538. http://dx.doi.org/10.1016/j.conbuildmat.2023.130538.

[10] Wei J, Jia Z, Wang Y, Jiang Y, Miao Z, Zhou Y, et al. Enhanced thermoelectric performance of low carbon cement-based composites by reduced graphene oxide. Energy Build 2021;250:111279. http://dx.doi.org/10.1016/j.enbuild.2021.111279.

[11] Kumar C, Gaur A, Rai SK, Maiti P. Piezo devices using poly(vinylidene fluoride)/reduced graphene oxide hybrid for energy harvesting. Nano-Struct Nano-Objects 2017;12:174–81. http://dx.doi.org/10.1016/j.nanoso.2017.10.006.

[12] Triana-Camacho DA, Quintero-Orozco JH, Mejía-Ospino E, Castillo-López G, García-Macías E. Piezoelectric composite cements: Towards the development of self-powered and self-diagnostic materials. Cem Concr Compos 2023;139:105063. http://dx.doi.org/10.1016/j.cemconcomp.2023.105063.

[13] Vishart JL, Castillo-León J, Svendsen WE. pyEIA: A Python-based framework for data analysis of electrochemical methods for immunoassays. SoftwareX 2021;15:100720. http://dx.doi.org/10.1016/j.softx.2021.100720.

[14] Pan HH, Lai T-Z, Chaipanich A, Wittinanon T. Effect of graphene on the piezoelectric properties of cement-based piezoelectric composites. Sens Actuators A Phys 2022;346:113882. http://dx.doi.org/10.1016/j.sna.2022.113882.

[15] Al-Qaralleh M. Piezoelectric behavior of polarized fresh cement pastes under the effect of different direct current voltages. Results Eng 2022;14:100430. http://dx.doi.org/10.1016/j.rineng.2022.100430.

[16] Alamusi, Xue J, Wu L, Hu N, Qiu J, Chang C, et al. Evaluation of piezoelectric property of reduced graphene oxide (rGO)–poly(vinylidene fluoride) nanocomposites. Nanoscale 2012;4:7250–5. http://dx.doi.org/10.1039/C2NR32185H.