PAPER

Graphene: a frontier material

Graphene is a material that ignites the imagination of researchers and fascinates the entire scientific community since, right from the start, it represents the emblem of the possibilities of research. With its extraordinary features, in a very short time, it won the *ad honorem* title of "wonders material", opening a new historical era in the scientific progress of two-dimensional materials. The uproar aroused by graphene has been recorded precisely since 2010, following the awarding of the Nobel Prize in Physics to the two scientists of the University of Manchester, who isolated it, for the first time, from its constituent: carbon. The two physicists, Andrei Gejm and Konstantin Novosëlov, thus attested to the existence of a material that seemed to be a chimera until then. The study of graphene potential and its possible uses has never stopped from that moment. The empirical confirmation of graphene's existence has revolutionized the Physics world by influencing many other sciences and scientific disciplines like wildfire, including architecture. At the same time as the award of the Nobel Prize, the nanomaterial jumped to the headlines, exciting scholars, entrepreneurs, universities, and institutions. For instance, the European Union invested a billion euros in graphene research in 2013, establishing the Graphene Flagship, a new form of a joint and coordinated research initiative on an unprecedented scale that connects academia and industry.

Due to its exceptional physical properties, graphene can be used in a multitude of applications in different sectors: from engineering to medicine, from electronics to the energy industry. Graphene opens the way to a new era of high-performance materials, which heralds a future in which material performance will play an increasingly crucial role in more industrial fields, in relation to the urgent environmental issue we are experiencing.

State of the art and case studies

Building construction has also acknowledged the entry of graphene into its field of action. At the industrial level, there are already many types of graphene-based products on the market, such as self-repairing cement and the one that improves thermal insulation; anti-rust paints to protect steel or graphene-based mixtures for building 3d printing. For the most part, these are products that exploit the excellent physical properties of graphene, used as an additive, to enhance the performance of the primary building materials of our time (fig.1).

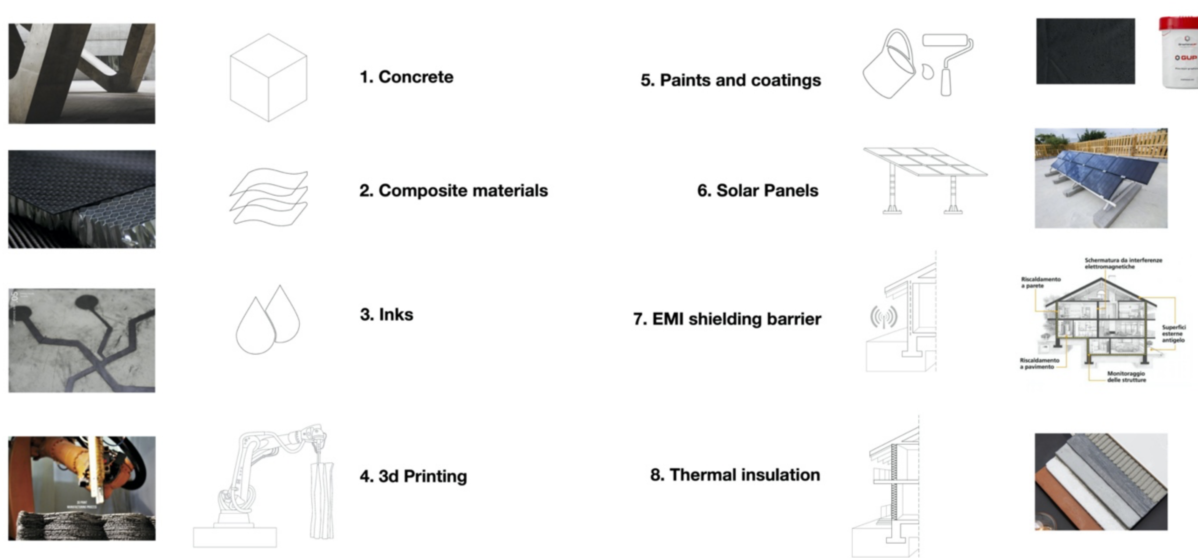

Figure 1. Graphene-based application and experimentations in building construction and architecture. Graphic representation. (Credits: Carla Bulone)

On the academic front, the most relevant projects come from the IaaC - Institute for Advanced Architecture of Catalonia - which being a Fab Lab, has produced a series of architectural projects as design driven experiments between 2016 and 2019 (fig.2).

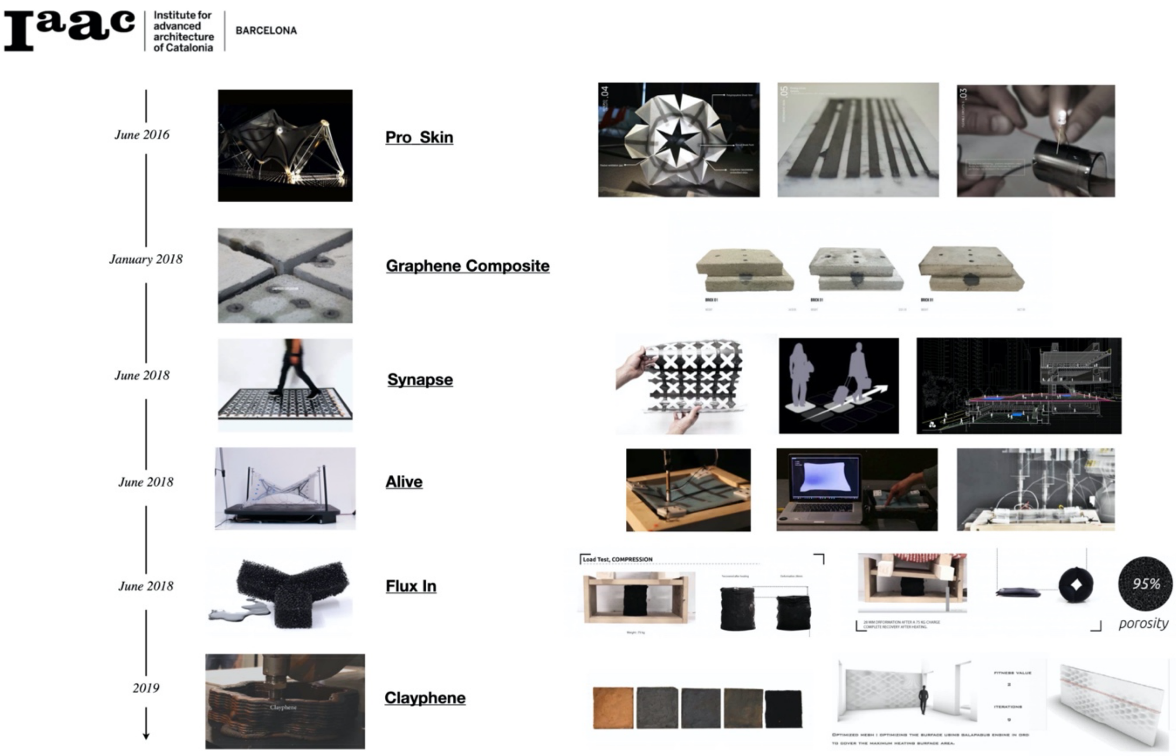

Figure 2. Projects with graphene by Institute for Advanced Architecture of Catalonia - IaaC . Graphic representation. (Credits: Carla Bulone)

Combining theoretical knowledge, design, and empirical experience, the IaaC projects examined are excellent design references on the topic under consideration, helping to reduce the distance between the architectural project and contemporary design needs, between thought and the product. In this sense, projects such as "Synapse", "Pro_Skin", "Graphene Composite", "Clayphene", use the material experimentation of graphene to develop alternative architectural solutions projected toward the future of architectural practice. Some of these projects are based on the design of smart materials and intelligent interfaces that are digital and physical at the same time, embedded into the materiality of the architectural prototype.

Research positioning

Following the references of the Spanish Institute, the research aims to fully understand how material experimentation, in this case with graphene, can influence design. By prototyping an architectural project, new uses and potentialities of current building materials can be defined, improving and innovating traditional architectural materials or designing new ones. The topic of materiality is the thematic focus of the research, on which the entire experimental activity has evolved up to now, starting from the use of nanomaterials in architecture in contemporaneity.

According to Hernández-Moreno and Solache de la Torre "in a document dealing with nanotechnological innovation in construction industry, Hanus and Harris (2013) establish that the application of nanotechnology can considerably improve the performance of traditional construction materials such as concrete and steel"; while "Ashby et al. (2009) present an introduction to the design of nanomaterials and nanotechnology from an approach of engineers and architects with an evolutionary perspective for nanostructured materials with protective applications in art and historical-heritage buildings. This work takes the context of design and the architectural or engineering approach into account to enable the right selection and assessment of the most suitable nano-products to solve certain problems in buildings and infrastructure, encompassing construction volumes, sort of building and construction components as well as environmental aspects, building processes, modulation, design flexibility, workforce and costs of the project"[1].

Therefore, this functionalistic approach, from problem to solution, applied to the final product, as a product of nanotechnology can be, is it not, in the same way, a design activity? At first glance, it would seem that the proliferation of nanomaterials in building construction is not part of Architecture, or rather "making architecture". In my opinion, however, the so-called "correct selection and evaluation" of the nano-products mentioned above, suggested by Ashby and co-authors, is an integral, if not fundamental today, part of the design activity of an architect as a civil engineer. The choice of the most suitable material for that specific context and function falls within the "critical and sensitive" decision-making and design sphere to which the designer is called to respond. Works of great recognition and architectural value,

[1] Hernández-Moreno, S., & Solache de la Torre, S. C. (2017). Nano-technological products in architecture and construction. Holos, 2, 34–51. https://doi.org/10.15628/holos.2017.5497

such as the architectures that characterized the rationalism movement in the last century, would lose their iconicity if they had been designed with different materials. In other words, and referring to the contemporary world, today the designer, architect or engineer, compared to the past, have at their disposal an almost unlimited range of material alternatives, in terms of the multitude of artificial materials (composite materials, ceramic materials, PCM phase change materials, etc.) and the increase in new and higher performing construction products on the market. Therefore, what really makes the difference is how the architect selects the range of material possibilities of the project and "puts them together". It is up to the designer to make use or not of a highly technological material, as the object of this research can be, to achieve a purpose, an objective, to solve a problem. It is up to the designer to understand if and how to use it once the extensive decision-making and design activity are over, including, among other assignments, the economic feasibility project with the evaluation of the client's budget, appraisal activities, cost-benefit analysis, and more.

Method and tools

The research method was basically divided into two key moments: the theoretical part, characterized by the qualitative method, and the experimental part. During the theoretical phase, in addition to the literature review and data collection, it was necessary to introduce a market analysis on graphene to understand which market segments and products are the most promising. Downstream of this, a clearer overview of the possible developments of a graphene prototype in architecture has emerged, excluding design paths that would not have brought significant progress to scientific research. In this regard, framing the most encouraging field of action has shown that the reference market segment is related to green building. The topic of environmental sustainability in architecture is, in fact, a collateral issue of the research, closely linked to the material development of the graphene application. A hypothesis for approaching the objectives of environmental sustainability in architecture could be to put the relationship between Project and Material back at the center, in which the performance of the materials acquires a priority value[2], this is what Sposito and Scalisi suggest in their work *Natural Material Innovation. Earth and Halloysite Nanoclay for a sustainable challenge*.

Therefore, following a methodological approach made up of a first review of the main literature about the use of graphene in architecture, market and feasibility analysis and the involvement of experts from different disciplines, such as chemistry and materials engineering, the research focused on the hypothesis of improving the performance of a natural building material. Based on the degree of the graphene technological advancement recorded in architecture to date, the choice of the "killer application" fell on the use of graphene as an additive in addition to raw earth as a building material, still in use for hundreds of years. Furthermore, raw earth is experiencing a period of flourishing rediscovery by architects who choose it for projects also of great visibility, such as Expo Milano 2015 (fig.3) and Expo Dubai 2021 (fig.4), confirming that this ancient construction technique has never been abandoned and, at the same time, choosing it as a valid material alternative to more polluting materials such as cement and concrete.

The resultant of this experimental approach will give birth to a new raw earth-based material with enhanced characteristics compared to the starting one. According to the initial predictions of the stakeholders involved, the addition of graphene will enhance the physical properties of the raw earth by virtue of a performance improvement (fig.5).

Figure 3: Morocco Pavilion for the 2015 Milan Expo by Oualalou+Choi

[2] Sposito, C., & Scalisi, F. (2019). Natural Material Innovation. Earth and Halloysite Nanoclay for a sustainable challenge. AGATHÓN | International Journal of Architecture, Art and Design, p. 59-72. https://doi.org/10.19229/2464-9309/572019

Figure 4: Morocco Pavilion for the 2015 Milan Expo by Oualalou+Choi

Figure 5: on the left rammed earth and raw earth bricks (credit: BC Materials company), on the right graphene flakes. (Credits: Branding Srl)

The material experimentation

The graphene masterbatch, a special water-based dispersion, is being tested together with three types of raw earth - ABS, T2 and TC - the most common types used today to obtain the optimal compositional mixture in terms of expected results. The tests are taking place at the Department of Chemistry, Materials and Chemical Engineering of the Politecnico di Milano, under Prof. Giovanni Dotelli's guidance and in cooperation with the raw earth expert Prof. Sergio Sabbadini - both Professors affiliated with the Polytechnic of Milan - while the graphene masterbatch was produced by the graphene manufacturer GrapheneUp, a leading European company and strategic partner of the present research. As an expert in nanotechnology and graphene, GrapheneUp supports the research activity through its knowledge of the experimentation of various graphene applications in different fields. His recent experience in the construction industry supports the idea that, already from the first tests, it will be possible to obtain quantifiable performance benefits. Preliminary tests have already started at the end of February 2022 and concern standard test protocols for new additives and earth characterization. While in March, a series of key tests began, mainly concerning the performance investigation of some physical properties. The testing phase will be followed by a phase of evaluation of the results, from which the limits of the research and the consequent purposes will be established. Once the framing of the material evaluation has been completed, the type of graphene-based material product developed will be defined exhaustively. However, some application hypotheses have already emerged at a preliminary stage (fig.6). At the same time, a set of tools and a methodology are being defined as the critical reading key to the experimental project. The introduction of the design-driven research approach, together with the prototyping activity, will be crucial and decisive for a valuable contribution. Some of the tests that will be performed in the laboratory are exploratory tests (such as the one on electromagnetic shielding) that arise spontaneously from the pure scientific spirit of the researchers involved. We do not yet know if some tests will be decisive or crucial; however, the research topic offers the opportunity to investigate new frontiers and open up new avenues for reflection. As the book suggests, *The new architecture of science: learning from Graphene* (Kostya S. Novoselov, Albena Yaneva, 2020)[3], the graphene discovery sparked researchers' enthusiasm, encouraging them to push beyond the limits known and studied so far.

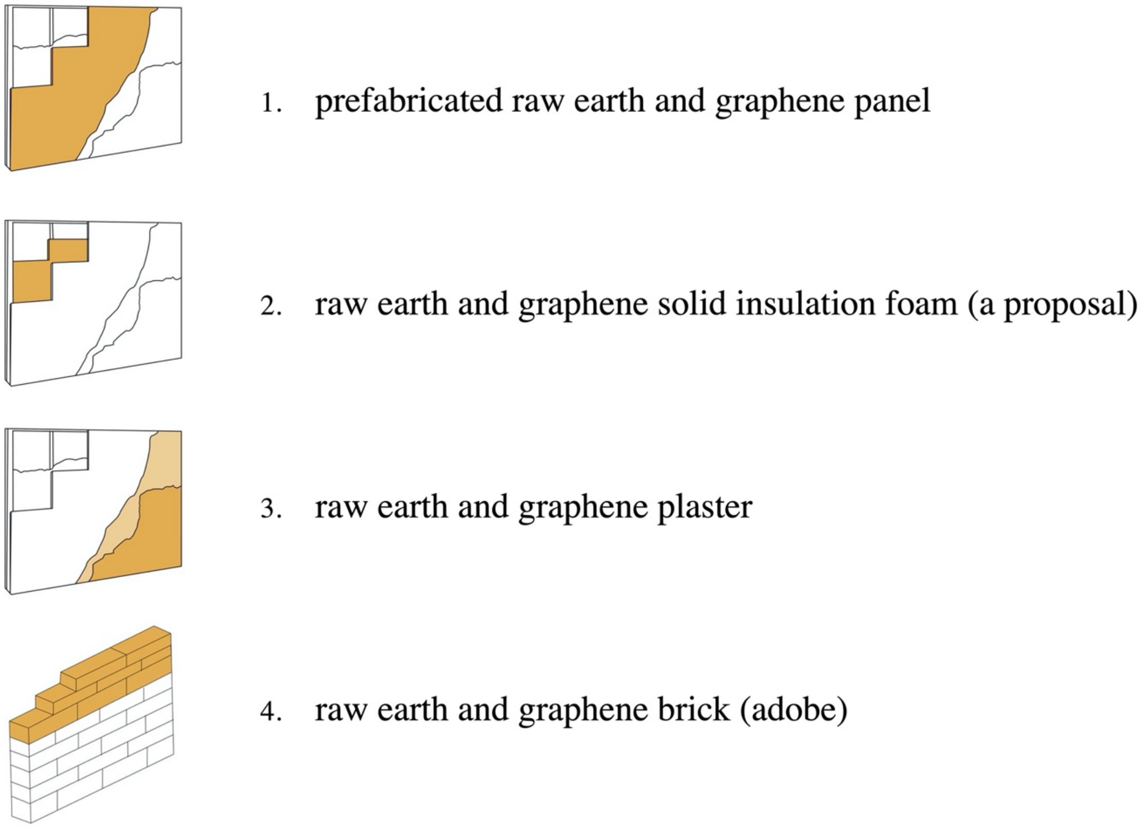

Figure 6: Graphic representation of the hypotheses on the graphene research application. (Credits: Carla Bulone)

Objectives

In conclusion, the research activity, through the study of graphene, aims to achieve the following objectives:

• contribute to the development of scientific research on the use of graphene in architecture;

• develop an industrial, architectural prototype with graphene as an outcome of the Ph.D. executive;

• create an unpublished *compendium* on graphene and architecture that can be interpreted as an introductory guide for future research on the subject.

With regard to the latter objective, intended as a further research outcome, the creation of a digital platform is being considered, conceiving as an open source in which to redirect, collect, and welcome scholars and researchers who work in the same research field. On the other hand, it may attract the interest of entrepreneurs who want to invest in this graphene application prototype.

Moreover, a final objective comes up regarding the impacts of developing a graphene application in architecture. In other words, the research also wants to encourage a more conscious use of non-renewable resources in architecture, to favor a rethinking of the entire supply chain of raw materials for the livelihood of the construction industry. And finally, the research aims to urge a return to the use of poor building materials to offer a contemporary interpretation by revisiting it as a precious resource, in line with recent promotion activities to safeguard and protect our ecosystem. One of all, Space Caviar is a collective of activists, researchers, and architects who, under the guidance of Joseph Grima, is proposing the Non-Extractive Architectures project, which became an exhibition program in Venice during the 17th Architecture Biennale, and then a book entitled *Non-Extractive Architectures: On Designing without Depletion*[4]. A multicultural and

[3] Kostya S. Novoselov, Albena Yaneva (2020). The new architecture of science: learning from Graphene (with Sir Kostya S. Novoselov). World Scientific Publishing Co. Pte. Ltd, Singapore, NJ and London. https://doi.org/10.1142/11840

[4] Space Caviar. (2021). Non-extractive Architecture. Vol.1. On Designing without depletion. Sternberg Press. Copublishers V-A-C Foundation, Moscow.

ambitious project for a new approach to Architecture based on long-term reflections, the use of material resources and the integration of community values in the construction industry.

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