Renew. Energy Environ. Sustain. **10**, 1 (2025)

https://doi.org/10.1051/rees/2024009

Renewable Energy and Environmental Sustainability

Available online at:
www.rees-journal.org

RESEARCH ARTICLE

OPEN ACCESS

Technologies for the reuse of demolition waste in the production of geopolymer-based building materials: prospects and opportunities

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Received: 20 February 2023 / Accepted: 11 December 2024

Abstract. In a climate change scenario that is increasingly affecting our daily lives, it is essential to rethink the reuse of existing resources and avoid the exploitation of raw materials. If we consider the stock of existing buildings in Italy, we cannot ignore the fact that most of them are in a state of decay or in need of major maintenance; the recovery or demolition of these buildings generates a considerable amount of waste that has a negative impact on the environment, from transport to disposal. A sustainable design approach can achieve interesting results in terms of economic, environmental and social impact. Starting from the final phase of the life cycle of buildings, this paper aims to show the possibilities of recovering traditional building materials such as cement, brick and tuff. The use of innovative production technologies will allow the reintroduction of these materials to the market, with consequent benefits in all aspects of the 'sustainability triad'. The aim of the work is to identify a practical, easy-to-use process for the production of eco-sustainable materials that, while retaining their intrinsic chemical-mineralogical characteristics, can be easily used in the context of the existing built heritage thanks to the compatibility between these new materials and the pre-existing substrate. The innovative results obtained as part of an international research project show how the use of demolition waste for the composition of geopolymer mixtures allows the reuse of large percentages of construction waste, while guaranteeing the mechanical performance of materials produced with traditional techniques, which have a high level of emissions; the production of geopolymers allows an 80% reduction in emissions compared to the production of Portland cement. The paper is intended to serve as a starting point for further in-depth application of the mixtures produced and to provide reflections and future research directions.

Keywords: Construction and demolition waste reuse / geopolymers / innovative eco-sustainable materials / recovery technologies

1 Introduction

The environmental emergency and climate change have become a highly topical issue that cannot be ignored. The indiscriminate use of resources, energy consumption and unsustainable designs have led to a redefinition of the criteria and policies needed to guarantee environmental protection and standards of comfort and well-being. The construction industry, which accounts for one third of the EU's total energy consumption, is part of this scenario, where demolition activities play an important role in the final balance in terms of waste materials produced. In fact, these materials account for about 1/3 of the total waste generated in the European Union. The category of inert materials has the highest percentage weight, reaching 75–80% of the total. In Mediterranean countries such as Spain or Italy, waste from ceramic products such as bricks or tiles accounts for about 54% of the construction and demolition waste (C&DW) generated. Analysing the data from the ISPRA reports, we see that the values considered at the beginning of the study, three years ago, for the period 2015/2016, have increased significantly in the following three years. Especially in 2019. Despite the increase recorded, according to the ISPRA Waste Report 2018 and 2021, the percentage set at 70% will be exceeded in 2016 and 2019. However, this value has to be assessed with a certain degree of uncertainty due to a non-exhaustive data collection, which is determined by the percentage of unreported or illegally managed waste [1].

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For this reason, the EU has identified the CDW stream as a priority for action. Identifying CDW recovery as an attractive alternative in the fight against climate change and environmental problems, integrated and linked to industrial activities.

Achieving these objectives requires a high level of investment in innovation and cannot be separated from the effectiveness of the financial instruments put in place. Since 1992, the LIFE programme, the Financial Instrument for the Environment, has been dedicated to promoting projects aimed at protecting the environment by conserving resources and developing new methods.

It identifies seven areas of intervention, and waste management falls within the environment and efficiency area. Of the thirty-two projects on the theme of "Waste – Construction and Demolition Waste" awarded between 1994 and 2018, the largest number came from Italy and Belgium (each of the two countries received five funded projects) [2].

To protect raw materials and the environment, reduce emissions and waste, and improve the quality of life, it is necessary to rethink sustainable design, introducing recycled materials with innovative solutions.

This international research project, developed under an international co-directorship between the University of Naples Federico II and the Polytechnic University of Madrid, is the result of interdisciplinary work in the scientific fields of Technical Architecture and Materials Science and Technology, and introduces a new type of building material, obtained from construction and demolition waste, to be introduced to the market in a circular economy perspective, focusing on the application of these materials not only in new projects, but also in the rehabilitation of existing buildings; In this sense, there is a need to reintroduce these "new secondary km0 materials", which are compatible not only from a formal and technological point of view, but also from a material one.

Therefore, the main objective of the work is to study the possibilities of recovering building materials in a sustainable way in the production of prefabricated building components by alkaline activation with sodium hydroxide and silicate solution [3] The applied part of the research focused on the production of samples, starting with the selection of waste materials, the determination of the performance composition and, finally, the evaluation of the properties of different samples.

2 New geopolymer materials

An analysis of the state of the art has shown that while the initial focus was on quantitative recovery, there is now an increasing trend towards qualitative recovery in terms of both function and environmental impact. In the present work, it was therefore decided to study a new type of binder called 'geopolymers', materials based on alumina-silicate. The suffix 'geo' indicates that geopolymers simulate natural rocks in terms of chemical composition and mineralogical structure, of which they exhibit the main properties such as hardness, chemical stability and durability [4]. The term polymer, on the other hand, indicates the type of consolidation process known as 'geopolymerisation'.

The production of geopolymers is one of the most innovative possibilities in recent years. Geopolymers are inorganic materials artificially produced from reactive aluminosilicate materials dissolved in a strongly basic environment. The term geopolymers refers to the polycondensation process, typical of polymers, by which these materials are obtained, emulating the chemical composition and mineralogical structure of natural stone compounds, of which they have the main properties such as hardness, chemical resistance and durability. These new materials are produced from the powder of the raw material whose compatibility with the construction equipment on which they are to be used is of interest. They are no longer mixed with water, as in the traditional technique, but with an alkaline solution that takes the form of a gel in the initial phase and then hardens. The curing temperature of these materials can be very low, if not at room (operating) temperature, which makes them very interesting from the point of view of environmental sustainability. The first person to talk about geopolymers was the scientist Davidovits, who invented the term 'geopolymers' in 1978 to refer to inorganic polymers, and who theorised about their use in the construction of the pyramids of Giza, believing that it was unlikely that the large blocks that made up the structure would have been used on the building site, as the theory generally accepted today suggests. According to the researcher, the individual blocks were made on site by mixing: a marly limestone, mixtures of natron (Na_2CO_3), water and lime (CaO) [X]. These materials have good mechanical, thermal and chemical properties such as: high compressive strength, good fire resistance without emission of harmful gases and excellent resistance to chemical agents. They also have low shrinkage during drying, good adhesion properties, low production costs with the possibility of using waste materials and an excellent surface finish, making them easy to cast in moulds for the reproduction of relief elements. These characteristics make them particularly interesting for the production of ceramic coatings and materials, but also for the production of new binders and mortars for fixing terracotta or stone elements, for the restoration of damaged parts and for grouting, as well as for use in the field of cultural heritage, precisely because of their ability to preserve the chemical-mineralogical characteristics of the raw material used; as stated in the 1989 Directive, with regard to masonry, "the use of binders similar in all respects to those used in antiquity is to be preferred, avoiding the use of cement mortars"; although what is quoted refers to point C. 1.1.9 on "Interventions in an archaeological context", the concept can and must be extended to the cultural heritage, which requires applications using materials compatible with those used in construction. These interventions do not necessarily have to be extensive, involving replacement or complete reconstruction, but can also take the form of localised interventions aimed at improving the behaviour of the construction apparatus and the functionality of the elements.

Fig. 1. Samples based on bricks waste.

In order to understand their diffusion, an analysis of patents related to geopolymers applied to waste reuse was carried out. In particular, the patent scope search yielded 51 results covering the period from 2012 to 2021, while the Espacenet Worldwide search identified 63 patents published between 2009 and 2021. What emerged from all of them was the characterisation of geopolymers as an alternative for reducing emissions and energy consumption, while respecting the properties of the mixtures and ensuring the achievement of remarkable mechanical performance; in fact, the production of geopolymers allows an 80% reduction in emissions compared to the production of Portland cement.

3 Materials and methods

The research was carried out at DICEA (Department of Civil, Building and Environmental Engineering – University of Naples Federico II) and ETSEM (Escuela Técnica Superior de Edificacion – Universidad Politécnica de Madrid). In this way, an interdisciplinary work programme has been developed in the scientific fields of technical architecture and materials science and technology, with the aim of exploring the technical and technological possibilities of reusing materials from construction and demolition activities and reintroducing them into the construction market.

The experimental plan to determine the feasibility of this new type of building material obtained from building and demolition waste is divided into eight phases:
– State of the art.
– Definition of objectives.
– Design of experimental activities.
– Analysis and definition of materials.
– Chemical analysis.
– Physical and mechanical tests.
– Data processing.
– Proposals for technological applications.

The choice of materials has been made on the basis of those produced in larger quantities, taking into account the environmental impact of these percentages in the final stages of the life cycle of buildings, as well as the greater demand in the new construction market; for this reason, the materials most frequently used in the Campania and Madrid areas and in the construction sector in general have been analysed, produced and tested: tuff, brick and concrete.

The tuff used came from blocks of Neapolitan yellow tuff and blocks of Viterbo tuff, measuring approximately $37 \times 25 \times 11$ cm. The blocks used in the first phase were crushed by hand; the resulting material was then crushed and the powders were sieved to select the correct grain size fraction. The cement-based material selected came from the segmentation and demolition of the plaster of the façade of a building in the city of Naples. The material already had a very fine grain size, so it was directly screened to weigh it down to the desired fineness. As for the bricks, the material came from a retailer of materials recovered from construction and demolition activities. The original waste material was of a different particle size composition to that selected for the experimental tests, so it was screened and divided into the required weights of the appropriate particle size fractions. A sodium silicate (SS) solution (Na_2O 8.15%, SiO_2 27.40%) with $R = 3$, supplied by Prochin Italia S.r.L. (Caserta, Italy) and a 10 M sodium hydroxide solution, prepared by dissolving NaOH pellets (NaOH 98%, J.T. Baker) in double-distilled water, were used as alkaline activators.

Forty-five prismatic specimens, forty-nine cubic and cylindrical specimens and six sample tiles were produced in the laboratory from these demolition wastes. In order to test the potential of reusing waste materials in a geopolymer mix, several experiments were carried out on samples made from C&D waste at 60 degrees for 3 days Figure 1.

In particular, geopolymerisation tests, flexural and compressive strength tests and immersion and capillary absorption tests were carried out [5] Figure 2.

Fig. 2. Immersion and capillary tests.

4 Conclusion

The results showed that there is an enormous potential for the reuse of raw materials used in the production of geopolymer-based building materials [6]. In particular, it was found that materials made from cement give remarkable results from a chemical point of view for geopolymerisation and appreciable results from a mechanical point of view, materials made from tuff have some difficulties in geopolymerising at high concentrations, but it is possible that the development of a different mixture offers good prospects for use, especially in applications where compatibility with the tuffaceous material constituting the buildings is essential. The materials produced by the bricks give optimum results in terms of geopolymerisation and performance. The flexural and compressive tests on the first three prisms produced with 100% fine-grained cocciopesto gave a maximum strength value of 2.85 ± 0.73 MPa and 5.34 ± 0.66 MPa, respectively. In order to have an idea of the possible applications, some of the experimental results obtained were compared with those present in the literature for different types of building materials comparable in terms of mechanical behaviour [7,8]. In particular, several traditional building materials, such as lightweight gypsum and natural hydraulic lime (NHL), were selected as terms of comparison together with different types of geopolymers and sustainable building materials produced from different types of waste. On the basis of these results, it can be concluded that the materials produced with geopolymer-based materials have good physical and mechanical properties, comparable to those produced with traditional technologies, and represent an important alternative to current binder production systems due to their potential to reduce emissions and energy consumption, thanks to low production temperatures, while respecting the properties of the mixes, thus ensuring the use of compatible materials that can also be used in the field of restoration of existing heritage. Thanks to its environmental and physico-chemical properties, the field of application is very wide; it could concern, for example, consolidation with injections of compatible material [9], or cladding as a prefabricated material, or large-scale distribution as a raw material. The production of geopolymers represents a highly innovative possibility for the reuse of a variety of solid waste materials, with particular efficacy when utilised in conjunction with aluminosilicate and clay waste. Following an analysis of the potential and eco-compatibility of these new materials produced from construction and demolition waste, a decision was taken to focus on applications relating to the recovery of the built heritage and of the territory and its surroundings [10].

The conservation of heritage is not merely a matter of preserving historical, cultural and landscape value; it is also a means of promoting a distinctive economic resource, fostering social development and protecting the environment. In this regard, the European Union is advocating for the intelligent development of environmental, accessibility, and sustainability issues, emphasizing the necessity for the identification of "pragmatic" approaches. It is thus imperative to pursue an approach aligned with the principles of circular economies, whereby conservation is not merely regarded as a constraint, but rather as a catalyst for re-functionalising and redeveloping spaces in innovative ways, while upholding and enhancing the intrinsic value of the territory [11].

The eco-sustainable and chemical-physical properties of the materials used, such as SS, and their low cost mean that they can be used in a wide variety of applications. These include the consolidation of structures with injections of compatible material and the covering of structures with prefabricated material. They can also be used in large-scale retail trade as a raw material.

Acknowledgments

The author would like to thank the whole group of the Applied Chemistry Lab @DICMaPI of the University of Naples Federico II, in particular Ilaria Capasso, Barbara Liguori and Domenico Caputo, for their help throughout the Ph.D. programme, as well as for their assistance in the laboratory activities and in the analysis of data and results. The author also thanks Mercedes del Rio Merino for her hospitality at the T.E.M.A. Lab of the E.T.S. de Edificación and for the work done together at the Universidad Politecnica de Madrid. It is important to express special thanks to the Med Green Forum Committee for the special mention of the doctoral work in the MGF Thesis Award, of which this article constitutes a presentation. All the results of the doctoral work have been published in a monograph text written by the author.

Funding

This research received no specific funding.

Conflicts of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Data availability statement

The data that support the findings of this study are available from the author.

Author contribution statement

The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

References

1. Centro Nazionale per il Ciclo dei Rifiuti, dell'Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA). ISPRA, Rapporti n. 285/2018 Giugno 2018
2. G. D'Angelo, M. Cannaviello, Da rifiuto a risorsa: Il contributo dell'Italia al programma LIFE, in *Proceedings of the IV Convegno Internazionale PRE/FREE – UP/DOWN – RE/CYCLE* 2021, edited by A. Baratta (Anteferma, 2021), pp. 65–72
3. B. Liguori, I. Capasso, M. De Pertis, C. Ferone, R. Cioffi, Geopolymerization ability of natural and secondary raw materials by solubility test in alkaline media, Environments **4**, 56 (2017)
4. D. Caputo, B. Liguori, G. D'Angelo, M. Fumo, Materiali leganti: tradizione e innovazione per un'edilizia eco-sostenibile e bioregionale, Bioregionalismo ed edilizia sostenibile, edited by L. Buoninconti, P. De Joanna, A. Falotico (LucianoEditore, 2020), pp. 119–135
5. G. D'Angelo, M. Fumo, M.d.R. Merino I. Capasso, A. Campanile, F. Iucolano, D. Caputo, B. Liguori, Crushed bricks: demolition waste as a sustainable raw material for geopolymers, Sustainability, **13**, 7572 (2021)
6. G. D'Angelo, From Demolition to Reuse Innovative Techniques for the Recovery of Construction and Demolition Waste Materials (LucianoEditore, 2022)
7. I. Capasso, F. Iucolano, Production of lightweight gypsum using a vegetal protein as foaming agent, Mater. Struct. Constr. **53**, 1–13 (2020)
8. P. Villoria Sáez, M. del Río Merino, E. Atanes Sánchez, J. Santa Cruz Astorqui, C. Porras-Amores, Viability of gypsum composites with addition of glass waste for applications in construction, J. Mater. Civ. Eng. **31**, 04018403 (2019)
9. G. D'Angelo, I. Capasso, A. Santo, B. Liguori, *Potential use of alkali-activated materials in naturalistic engineering*, SMC – Sustainable Mediterranean Construction. Land Culture, Research and Technology, Vecchi problemi e nuove costruzioni, I terrazzamenti della Costa d'Amalfi, paesaggio culturale UNESCO, edited by M. Fumo, G. Trinchese, G. D'Angelo, V. Vitiello, Special Issue n. Six (LucianoEditore 2021)
10. I. Capasso, G. D'Angelo, M. Fumo, M. Del Rio Merino, D. Caputo, B. Liguori, Valorisation of tuff and brick wastes by alkali activation for historical building remediation, Materials (2023)
11. G. D'Angelo, C. Lombardi, M. Fumo, V. Guarino, Percepire i centri minori: nuove metodologie di recupero, CIRICE 2020, LA CITTÀ PALINSESTO, IX Convegno internazionale, Napoli, 10–12 giugno 2021 (2021)

Cite this article as: Gigliola D'Angelo, Technologies for the reuse of demolition waste in the production of geopolymer-based building materials: prospects and opportunities, Renew. Energy Environ. Sustain. **10**, 1 (2025), https://doi.org/10.1051/rees/2024009