INNOVATIVE MATERIALS AND TECHNOLOGIES FOR A NEW ENVELOPE SYSTEM IN THE SUSTAINABLE REFURBISHMENT OF EXISTING BUILDING STOCK

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Summary

The theme of energy efficiency must nowadays be correlated to new requirements for the adaptation of existing buildings to performance standards. This issue must be further addressed within the domain of technique, through the contribution and methods offered by scientific innovation. The strategy proposed here aims to investigate, optimize and promote new construction technologies to face the problem of energy retrofitting for existing building stock, combining innovative assumptions and tools, customised on different building typologies.

The on-going research carried out by the *CIRI – Centro Interdipartimentale di Ricerca Industriale* (University of Bologna) aims to optimize the exploitation of innovative sustainable materials to develop a continuous envelope system for existing buildings that could guarantee high performance. The project seeks to use a new class of materials, named geopolymers, which are highly regarded for their excellent physical, mechanical and thermal properties. The technological solution proposed is the application of an ecological material layer, obtained through the geopolymerization process of ceramic industrial waste, in order to generate a new envelope system. The direct exploitation of geopolymer-based products (plasters and panels) has been envisaged, and this geopolymerization technology would seek to optimize energy efficiency in the architectural design through the recycling of industrial ceramic waste.

Keywords: technology, architectural design, envelope system, materials recycling, geopolymers

1 Introduction

One of most frequent and complex problems that the building construction sector has to face concerns the refurbishment of the existing building stocks, not only from the functional and architectural point of view, but also for the purpose of energy efficiency.

Within the member countries of the European Union, the construction sector contributes on average about 21 % to the GDP, creating a high consumption of non--renewable resources and high environmental impact. When viewing the total consumption of these resources, the construction sector annually accounts for the use of more than 40 % of non-metal mineral, over 25 % of timber, slightly less than 20 % of water and about 40 % of burned energy resources. The use of renewable non-petroleum-based materials, derived from the reusing and recycling of production waste, has enormous potential to contribute to the reduction of CO_2 consumption, and to serve as the primary energy in the production of new construction materials.

Reuse and renovation of the pre-existing building stock represents a key factor for sustainability, highlighting that a building with a long durability and reusability may correspond to a high long-term productivity of resources. The energy efficient refurbishment of these buildings serves both to reduce the consumption of resources and raw materials, which in most cases have reached only half of their life cycle, and to extend the building's long term functionality. In addition, these rehabilitation interventions would offer an alternative to the high costs and consumption inflicted by the demolition of existing building and the reconstruction of new buildings.

The overall heat loss from a building is due to transmission, ventilation and infiltration through the envelope. Transmission, which usually accounts for the largest percentage of heat loss, can be roughly divided into that which loses heat through the use of transparent envelopes, non-transparent (opaque) envelopes, and thermal bridges. The percentage of heat loss of each of the three above mentioned categories of building components is variable, depending on the type of envelope and the age of construction. In general, the recent increasing use of transparent building components and the reduction of thermal bridges, due to a more accurate design, have significantly increased the overall thermal resistance of the envelope. In the last 20 years U-values for new external walls have been reduced by two thirds, approximately from 0.9 $W.m^{-2}.K$, to less than 0.3 $W.m^{-2}.K$.

Unfortunately in most 20–50 years old buildings, especially those utilising reinforced concrete construction and masonry construction, discontinuities are frequently found in the envelope insulation and air barrier systems. External coatings are the common solution to improve thermal efficiency in rehabilitation projects, their selection mainly depending on cost. Other considerations from a design perspective include thermal conductivity, durability, and aesthetic value. Simple coatings are used in residential units; in Mediterranean countries – e.g. in Italy – stucco work on thermal coating is the most common finishing after refurbishment. In some cases, in the interest of aesthetic sensibility, ventilated façades are utilised commercial and public buildings. Increasingly more considerations is being given to the environmental impact of building materials; and for this reason, more expensive and lower performance natural and/or recycled products are being used, replacing new synthetic materials in insulation.

2 Objectives

In the domain of refurbishment interventions in existing buildings, one of the primary objectives concerns the energy efficiency of the façades solutions. A key element of this refurbishment design strategy involves the juxtaposition of the second skin to the existing envelope building, with the aim of controlling energy consumption during cold season.

Our goal is to supply tools and methods for designers who operate by using eco--sustainable solutions for the improvement of the energy performance by volume increasing. The project aims to develop a methodology for the whole design process of a "dynamic" envelope system, supported by geometric survey systems and computational CAD-CAM tools. Thus this dynamic construction element will be able to interact with the internal and external environment through the interoperability of its façade components, in relation with the variability of the required performances.

The research focuses on the need of continuity in new technological envelope systems, which could bring high energetic performances, as well as a good structural behaviour. In particular, the study of this innovative technology, based on the preliminary analysis of the current conservation conditions of the existing buildings, investigates the possibilities offered in recycling geopolymer-based materials, such as the waste materials yielded by brick production.

The project is aimed in developing an integrated environmentally friendly solution to the design of building envelope tailored to each specific situation, thus adaptable to the morphology of the existing building block, which would respect both the requirements imposed by current regulations, and the needs of architectural design.

3 Innovative technology for a new continuous envelope system

Modern technological evolution within the domains of building construction and materials technology allows designers to reassess the traditional concept of envelope building as a rigid separation barrier between inside and outside, to conceive it like a dynamic diaphragm, according to internal and external solicitations.

In the domain of refurbishment interventions of existing building stock, one of the primary objectives concerns the function and energy efficiency of the façades solutions, which are composed of surfaces that could be vertical, horizontal or inclined, opaque or transparent.

These interventions are related to the improvement of the thermal insulation of the envelope, the reduction of the thermal bridges, the upgrading of windows, and the process of mitigation through natural ventilation and green integration. Within this framework, it is important to conceive a design strategy, which serves to juxtapose the second skin to the existing envelope building, with the aim of controlling energy consumption and reducing heat loss during the cold season.

The research investigates the possibility of creating a "continuous envelope system" (T. Herzog, 2004), meaning a second skin tailored to the existing shape, constituted of a bearing structure linked to the existing façade, which functions in the double role of containment and frame for the thermal insulation material. When this material, which is poured in the form of a fluid plaster, reaches its hardened state, it can be combined with the existing façade in order to create an integrated envelope system possessing an efficient thermal and structural behaviour.

The transition from a non-load-bearing “curtain wall system” – composed by the assembly of different elements connected with each other – to a “continuous envelope system” – constituting of a unique, close-fitting, integrated skin attached to the existing façade – leads to the maximum reduction of the heat loss bridges in relation to the discontinuity points of the building.

In the following paragraphs, the principal properties of the innovative solution here proposed will be outlined, analyzing the two main components: the load-bearing frame structure and the thermal insulation material integrated with it.

3.1 The frame structure model

Our structure is designed as a three-dimensional frame structure containing the geopolymer-based insulation material, anchored to the existing wall through a mechanical punctual fixing system.

The frame structure is self-supporting, resistant to the strength of tension and compression, and serving a double function: improvement of the structural behaviour (absorption of the horizontal forces) and containment for the thermal insulation material aimed to upgrade the energetic performances (new layer composed by a high performance vitreous-base material).

The management of the phases of analysis, design and implementation, would involve the use of computational control tools in creating tailored architectural solutions, adapted to the different morphologic and constructive characteristics of the existing block. Thanks to the Laser Scanner technology for the metric survey and thanks to the CAD-CAM technology, associated with the CNC machines for cutting and shaping the prefabricated parts, it is possible to simplify the process of information transfer from the early design phases to on site construction.

This approach allows to overtake the widespread use of design criteria based on a strong formal simplification of the architectural solutions, set up by the assembly of flat-linear elements for the building envelope, leading to the development of more complex forms better able to fit in with the spatial typological configuration. The digital model is accomplished through parametric programming software (*Rhinoceros+Grasshopper*), interfacing with machines for the industrialized production of building components.

This generative design represents an advanced approach for architectural design, as a nonlinear dynamic system to manage the complexity of the construction. The performative research leads to the development of adaptive structural components and their aggregation configurations. The methodology is founded on the concept of generative component, related to the possibility of creating models operating directly on the geometry, through the input of forms and algorithms. The “dynamism” concerns the variability of the constructive system, according to its orientation and internal distribution: the different materials layers change their composition, size and characteristic properties, to best meet performance requirements of the building. Therefore, this new parametric architectural design that permits to control of all the factors to be taken into account, offering all the while a greater freedom of form, aims to promote this innovative production process into the industry and design world, with prototypes to be reproduced to scale by using a high precision 3D Printer.

The research conducted thus far led to the design of a grid structure composed of hexagonal cells. This geometrical shape, widely present in nature, presents a great potential for the modulation of the façade surfaces: it allows to obtain a surface tiling corresponding to the geometric optimization of the space, according to the principle of the closest packing (C. F. Gauss, 1831). The forms found in nature are always generated by structures, which are strictly related to the functions which will be performed. This process of creation found in natural structures is governed by the requirements of minimum energy, which is manifested by the principle of the closest packing, which consists in partitioning a space with the most economical subdivision and combination of complementary geometries. Considering the infinite partitioning systems, the circle and the sphere (which represent the most economical geometrical shapes for the optimization of the two-dimensional and three-dimensional space) do not correspond to the best closest packing configuration. The closest packing with the highest density is found in the partitioning of a surface into regular array of repeated identical hexagons (J. H. Conway, N. J. A. Sloane, 1993). The most common and "sublime" example of closest packing appears in the honeycomb produced by bees: "this system, a plan of regular hexagons, permits to stock the greatest amount of honey with the least amount of beeswax", with the mininum amount of necessary energy exerted in construction (P. Pearce, 1990).

In both biology and architecture, the process of optimization describes the synthetic search for the best state within a model; the outcome will be determined by the requirements and goal which are being pursued. The computer is used to search a defined solution space and to mould the innovative material by responding to strains and performances. The geometrical tessellation of the innovative envelope system is achieved through the experimentation of different optimization methods in order to find structurally economical forms, to smartly resolve the panellization of surfaces, to minimize the size of structural members and to resolve the perfect thinness of the thermal insulation layer (J. Burry, M. Burry, 2010).

Furthermore, a hexagonal mesh allows for the modelling of surfaces with a higher degree of deformability and curvature, in order to reach an innovative envelope adaptable to the existing building geometry. The unlimited formal possibilities offered by the proposed constructive solution can also be explored from the analytical point of view, through the creation of mechanicals and thermal models.

The following images depicting our first prototype, based on the assembly of prefabricated elements designed by parametric programming software, illustrate one of the viable strategies to develop architecturally engineered materials and structures.

The first sample shown employed a geopolymeric material obtained by using ceramic residues as a precursor, whose more precise definition (exact composition, molar ratio and amount of the alkaline solutions) will not be specified in this paper. The raw materials used for the synthesis of geopolymers were ceramic residues being produced by ceramic companies based the region of Emilia Romagna, located in the northeast of Italy. Sodium silicate and sodium hydroxide solution were used as alkaline activators.

The frame structure model was created with the use of a 3D Printer, which used a proper mixture of gypsum powder and resin for the additive manufacturing process. The epoxy resin was selected in order to provide the best compromise between adequate stiffness and high strength in the model **(Fig. 1)**.

The geopolymer paste was prepared by mechanically mixing the ceramic waste and the alkalin solutions for approximately three minutes at low and medium speeds (Hobart mixer). After the assembly of the first horizontal array of elements, and their anchoring to the panel (simulating the existing façade), the prepared paste was cast vertically inside the holes belonging to the upper side of each module, by using the structure as a formwork. The cast process lasted until the filling of all the hexagonal cells by the geopolymeric thermal insulting paste was achieved, with the aim of simulating the real installation and set up process on the construction site. Then the process continued with the second array of 3D printed hexagonal elements, in order to complete the prototype **(Fig. 2)**. The final prototype was cured at room temperature for a 24 hours period, which was estimated to be the required time for a complete hardening.

(a) (b) (c)

Fig. 1 *Gypsum and resin model of the frame structure, realized by 3D Printer: the four components (hexagon side = 3 cm); back (b) and front (c) of the components assembly; the whole envelope system to be juxtaposed to the existing façade (c). The grid regularity and the thickness of the cells vary according to the geometry of the existing façade and to the thermal insulation requirements.*

Fig. 2 *Prototype: phases of the pour process to fulfill the hexagonal cells with the geopolymeric paste (light red colored), by using the frame structure as a formwork precedently fixed to the panel simulating the existing façade. The procedure allows obtaining a continuous new envelope system for the existing building as a high performance thermal insulting skin.*

Moreover the good workability of the mixture makes its application possible in both a prefabrication system, and in its direct application as humid paste on the building site **(Fig. 3)**. The versatility of the investigated geopolymeric paste serves to introduce an innovative family group of materials with the potential for great sustainable qualities. Future research will be focused on the chemical and mechanical study of the frame structure, which will be constructed using recycled materials with high mechanical resistance properties, according to research paradigms. A mathematical model of the geometrical system, which has been previously designed with parametric computational tools, will be created in order to study the mechanical and thermal behaviour.

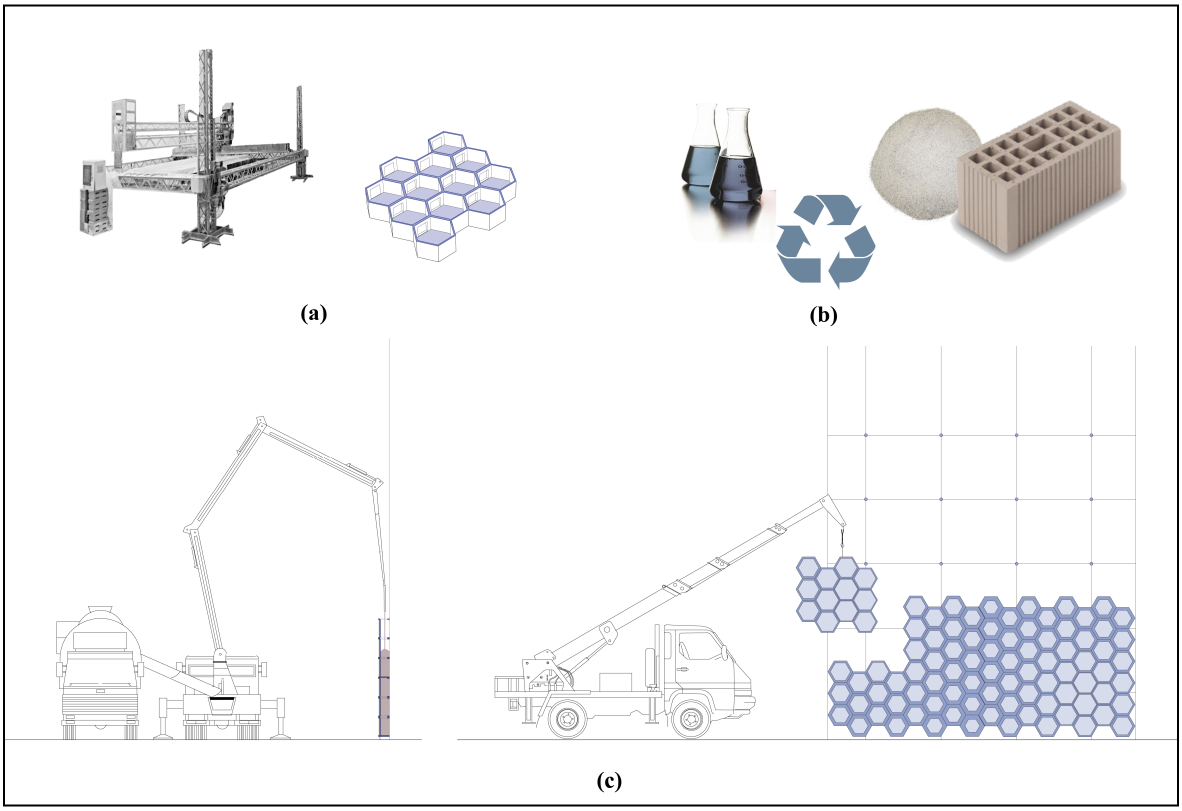

Fig. 3 *Simulation of the process of production: the panel composed by hexagonal cells are created by using CAD-CAM technology, associated with the CNC machines for cutting and shaping the prefabricated parts (a); the geopolymeric paste to be integrated with the envelope is produced by using material derived by bricks, combined with an activator solution containing a glass siliceous material, to definitely obtain a final product with excellent thermal performances (b); transportation of the prefabricated panels on building site, their installation and fixation to the existing façade and vertically casting of the geopolymeric paste, by proceedings by horizontal layers, from the bottom to the top.*

3.2 The geopolymer-based plaster as insulating material

Geopolymers are formed by alkali activation of aluminosilicate materials, e.g. metakaolin. The most popular activating agents are sodium silicate and highly concentrate sodium hydroxide solutions.

The geopolymerization mechanism includes three main steps (M. M. A. Abdullah, K. Hussin, M. Bnhussain, K. N. Ismail, W. M. W. Ibrahim, 2011):

- dissolution of silicon and aluminium atoms in raw material, generally metakaolin;
- re-orientation of the ions in solution;
- poly-condensation reactions leading to the development of inorganic polymers.

The most relevant innovation of our research is based on the use of ceramic industrial waste as starting materials, instead of metakaolin normally obtained by calcined natural kaolin. The idea is to save no-renewable raw materials and use waste generally dismissed to landfill in order to obtain sustainable final products. The aim is to design new geopolymer-based materials with versatile properties in order to have materials suitable for many purposes in different engineering fields.

Furthermore, most previously studied geopolymeric systems usually need a temperature higher than 25°C, thus necessitating energy consumption and limiting the potential applications of the final products despite showing good physical and mechanical properties. So one of the primary conditions for the successful outcome of this research is to ensure that the hardening process will occur at room temperature. It was discovered in early attempts that the selected ceramic waste used as a precursor can be activated at room temperature. Different formulations have been designed by modifying the molar ratio of the most important oxides (SiO_2, $Al2O_3$, Na_2O) directly involved in the geopolymerization process. Thanks to a good chemical formulation of the active components, it has been possible to control the workability and the density of the final products. In this way, the investigated material could be implemented for a large array of uses: spread on wall surfaces, cast in special moulds for tiles, or applied as traditional cement based mortar and concrete.

Preliminary results on the investigated systems have shown density values between about 1,00 $g.cm^{-3}$ and 1,7 $g.cm^{-3}$. In the following images **(Fig.1)** two samples are reported.

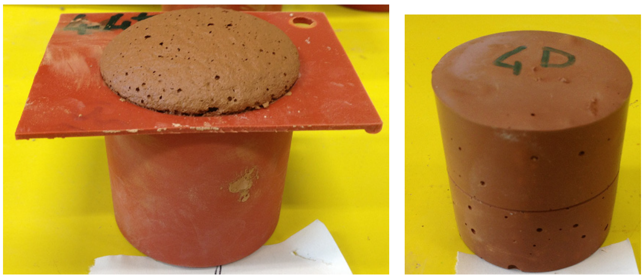

Fig. 4 *Samples with the lowest (left) and highest density (right) reached during the research.*

Thermal conductivity measurements are currently running on the more promising mixes. Regarding the power of thermal insulation in terms of conductivity λ, it is expected that the value is between the perlite foamy geopolymers λ, equal to 0,03 $W.m^{-1.}$ K^{-1} (V. Vaou, D. Panias, 2010), and the fired clay brick one, corresponding to 0,4 $W.m^{1.}$. K^{-1} (J. E. Oti, J. M. Kinuthis, J. Bai, 2010). Further researches are in progress to fully characterize the investigated geopolymer system in terms of mechanical and physical properties.

4 Conclusions

A new culture of sustainability must involve the use of sustainable materials in exterior insulation finishing systems, with an emphasis placed on durability and the capacity to age well; the minimization of the consumption of embodied energy; and flexibility and reversibility according to the future users' needs. Indeed, the practical and theoretical advances made through the interventions inspired by sustainability principles are easily recognizable in the field of the energy efficiency, with the growing reduction of consumption and the frequent use of renewable sources, and also in the field of materials technology, in terms of the potential energy used in the reuse and recycle of materials, and in the management of demolition waste.

In viewing the building as a complex machine, the design strategy of the most important building components, such as an envelope system, contribute to the overall energy sustainability, and serve to direct attention to the verification of the construction techniques, their installation process, and the application of materials and their operation methods.

The approach presented here allows designers to overtake the widespread use of design criteria based on a strong formal simplification of architectural solutions, leading to the development of more complex forms better able to fit in with spatial typological configuration and to guarantee a new thermal insulating continuous second layer for the existing envelope.

The geopolymer to be integrated with this envelope is produced by using material derived by bricks, combined with an activator solution containing a glass siliceous material; definitely the final product presents excellent thermal properties. Furthermore, this product presents a high resistance to chemical and weather agents and good mechanical properties even under extreme conditions.

Geopolymer presents a great additional value compared to the traditional materials used in construction, since it is composed mainly of raw waste materials, dried at room temperature, and since it has a density variable depending on the type of application. The conditions that characterize the drying and production process represent one of the main advantages of this geopolymeric product, owing to its high reduction of carbon dioxide emissions.

This research development could explore the variability of the final characteristics of our geopolymer-based feedstock, aiming to improve and specify the formulation according to specific requirements. Further researches of viable applications for this material in envelope system solutions are expected to open up new design methods in the field of sustainable refurbishment of recently constructed buildings.

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