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Research title

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

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Al potenziale nascosto che si trova in tutte le cose e che c'è in ognuno di noi.

"La felicità non viene da un lavoro facile, ma dal bagliore di soddisfazione che appare dopo il raggiungimento di un compito difficile che richiedeva il nostro meglio."

(Competition and Happiness - Theodore Isaac Rubin)

Al potencial oculto que se encuentra en todas las cosas y en cada uno de nosotros.

"La felicidad no viene de hacer trabajo fácil, sino del brillo de satisfacción que viene después de la realización de una tarea difícil que exigió de nosotros lo mejor."

(Competition and Happiness - Theodore Isaac Rubin)

To the hidden potential found in all things and within each of us.

"Happiness does not come from doing easy work but from the afterglow of satisfaction that comes after the achievement of a difficult task that demanded our best."

(Competition and Happiness - Theodore Isaac Rubin)

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Abstract

The environmental emergency and climate change have become a highly topical issue that cannot be ignored. The indiscriminate use of resources, energy consumption and designs lacking in attention to sustainability, have led to a redefinition of the criteria and policies needed to guarantee the protection of the environment and standards of comfort and well-being. The construction industry, which accounts for one third of the European Union'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 order 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 research work introduces a new type of construction materials obtained from construction and demolition waste to be introduced on the market in a circular economy perspective.

In order to verify the potential of reused waste materials in a geopolymer mixture, several experiments were conducted on samples produced at 60 degrees for 3 days from construction and demolition waste.

The results show that the materials produced have good physical and mechanical characteristics comparable to those produced with traditional technologies.

Based on these results, it can be conclude that geopolymer-based materials 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 mixtures and thus ensuring the use of compatible materials to be applied also in the field of rehabilitation of the existing heritage.

Premessa

L’emergenza ambientale e i cambiamenti climatici sono ormai un argomento di estrema attualità che non può più essere ignorato. L'uso indiscriminato delle risorse, il consumo di energia e progettazioni poco attente alla sostenibilità, hanno portato ad una ridefinizione dei criteri e delle politiche necessarie a garantire la salvaguardia dell'ambiente e degli standard di comfort e benessere. In questo panorama si inserisce l’industria delle costruzioni, rappresentando un terzo del consumo totale di energia dell’Unione Europea, all’interno della quale le attività di demolizione giocano un ruolo importante nel bilancio finale in termini di materiali di scarto prodotti.

Con l’obiettivo di tutelare le materie prime e l’ambiente, ridurre le emissioni e gli sprechi, e migliorare la qualità della vita, è necessario ripensare la progettazione in chiave sostenibile, introducendo materiali riciclati con soluzioni innovative. Questo Lavoro di ricerca presenta nuovi tipi di materiali da costruzione ottenuti dai rifiuti di costruzione e demolizione da introdurre sul mercato in un’ottica di economia circolare.

Al fine di verificare il potenziale dei rifiuti riutilizzati in una miscela geopolimerica, sono stati condotti diversi esperimenti su campioni prodotti a 60 gradi per 3 giorni a partire dagli scarti delle attività di costruzione e demolizione.

I risultati mostrano che i materiali prodotti hanno buone caratteristiche fisiche e meccaniche equiparabili a quelli prodotti con tecnologie tradizionali.

Sulla base di questi risultati, è stato possibile concludere che i materiali a base geopolimerica rappresentano un'importante alternativa agli attuali sistemi di produzione di leganti per il loro potenziale di ridurre le emissioni e il consumo di energia, grazie alle basse temperature di produzione, rispettando le proprietà delle miscele e garantendo così l’impiego di materiali compatibili da applicare anche nel campo del recupero del patrimonio esistente.

Resumen

La emergencia medioambiental y el cambio climático son temas de la agenda que no podemos ignorar. El uso indiscriminado de recursos, el consumo de energía y los proyectos poco sostenibles, han llevado a redefinir los criterios y las políticas necesarias para garantizar la protección del medio ambiente y los niveles de confort y bienestar. La industria de la construcción, que representa un tercio del consumo total de energía de la Unión Europea, hace parte de este panorama, donde las actividades de demolición juegan un papel importante en el balance final en lo que respecta a los materiales de desecho producidos.

Con el objetivo de proteger las materias primas y el medio ambiente, reducir las emisiones y los residuos y mejorar la calidad de la vida, es necesario repensar el proyecto de forma sostenible, introduciendo materiales reciclados con soluciones innovadoras.Este trabajo de investigación presenta nuevos tipos de materiales de construcción obtenidos a partir de residuos de construcción y demolición debido a la economía circular.

Para comprobar el potencial de los residuos reutilizados en una mezcla de geopolímeros, se realizaron varios experimentos con muestras producidas a sesenta grados durante tres días a partir de residuos de construcción y demolición.

Los resultados muestran que los materiales producidos tienen buenas características físicas y mecánicas comparables a las de las tecnologías tradicionales.

A partir de estos resultados, se pudo concluir que los materiales a base de geopolímeros representan una importante alternativa a los actuales sistemas de producción de ligantes debido a su potencial para reducir las emisiones y el consumo de energía, gracias a las bajas temperaturas de producción, respetando las propiedades de las mezclas y garantizando así el uso de materiales compatibles que también pueden aplicarse en el ámbito de la rehabilitación del patrimonio existente.

This thesis is divided into 7 chapters. At the end of each chapter can be found the partial conclusions and the bibliography for the individual chapter.

- **Chapter 1:** the chapter introduces the world of construction by considering the aspects of demolition and rehabilitation as necessary interventions to address the problems related to the conservation status of buildings. It focuses on sustainable development and the impacts of the construction industry on the environment by introducing the issue of waste from construction and demolition activities.
- **Chapter 2:** in this chapter, the objectives of the proposed research are defined according to what was concluded in the previous chapters.
- **Chapter 3:** the chapter frames the state of the art from a regulatory and design point of view for the management of construction and demolition waste. In the course of the discussion, it identifies the use of geopolymers as an innovative and eco-sustainable answer and proceeds to examine patents and applications.
- **Chapter 4:** the chapter deals with the methodology adopted, detailing the different phases of the research work. This chapter describes the materials selected, the preparations and the experimental tests carried out on the samples.
- **Chapter 5:** the chapter contains an analysis of the results from sample preparation to mechanical testing. Tests were carried out in the materials laboratory of the DICMaPI - Department of Chemical Engineering Materials and Industrial Production of the University of Naples "Federico II" and in the materials laboratory of the Department of arquitectural constructions and control of the ETSEM - Escuela Técnica Superior de Edificacion of the Universidad Politécnica de Madrid.
- **Chapter 6:** the chapter explores areas of application based on the results obtained. It proposes future research opportunities to be pursued in the areas of large-scale distribution, building materials production and maintenance. It contains an in-depth study of applications in the field of naturalistic engineering and a re-geopolymerisation test to reintegrate materials into the production cycle and give them a third life.
- **Chapter 7:** based on the partial conclusions of each chapter, conclusions of the experimental research project carried out in international joint supervision between the University of Naples "Federico II" and the Universidad Politécnica de Madrid are presented.

CHAPTER 1 Introduction

The construction industry accounts for one third of the total energy consumption in the European Union. Demolition activity is an important part of the construction industry due to the production of tons of discarded materials and the consequent environmental impact. [1] In Italy, when we talk about buildings, we have to consider the existing heritage resulting from the strong post-war residential expansion when people started to build indiscriminately, often neglecting the quality of the buildings, in order to quickly satisfy the high demand for housing. These are buildings with low energy performance which in many cases no longer meet social, technological and environmental requirements.

Today, a large part of the built environment is either in a state of serious decay or in an illegal building situation or, simply, as already mentioned, is unable to meet the new requirements of eco-sustainable living. These buildings, which consider demolition as the final phase of their life cycle, can be seen as storage of building materials as well as potential suppliers of waste materials, to be transformed into secondary raw materials.

By researching new techniques aimed to reduce waste and energy consumption, it is possible to evaluate the potential for possible reuse at the end of the building's life cycle, to build or rebuild respecting environmental protection policies and guaranteeing standards of comfort and well-being. [2]

Demolition or renovation? The choice can be difficult, considering the starting conditions and future scenarios. Demolitions are still an issue which is not widely considered. It is often relegated to the realm of illegal building, and does not stand out for the potential it actually offers. All we have to do is think of the environmental and anthropological advantages that derive from the demolition of the many ecomonsters and the possibility of reintroducing huge quantities of recycled material into the construction market.

Although there are many ways to regenerate a building, technology and the construction system can play a decisive role in the determination of its end-of-life phase, due to the costs of structural and energy renovation and adaptation. In addition, economic evaluations are supplemented, or sometimes preceded, by political, historical and social considerations. Therefore, the final phase of a building's life cannot always be indisputably determined; there are two possible scenarios that often emerge when faced with a condition of functional inefficiency: Demolish or Recover. Managing the last phase of a building's life cycle is a highly topical issue. Much of the building production of the twentieth century is no longer able to respond adequately to the social, structural and environmental needs that have undergone major changes over the last century. Faced with these conditions, there is often a big question about the final destination of these buildings: should they be rehabilitated or demolished?

The answer to this question often results in a condition of stasis. The life cycle of the building seems to crystallise at a crossroads, with the consequent and irremediable abandonment and decay of the construction. [3]

1.1. Environment and sustainable development

Environment and climate will be central to all European policies in the coming years. The European Green Deal [4] shows that the challenge of global decarbonisation by 2050 cannot be separated from the sustainability of the building sector through the transition from "zero energy building" to "carbon neutral building". This presupposes a radical change in the way buildings are designed and constructed, leading to the implementation of the circularity of the entire process, controlling inputs and outputs throughout the life cycle, without neglecting the end-of-life phase and therefore the management of construction and demolition waste. [5] Increased awareness of environmental responsibilities in the building sector has led to a new design approach and a rethinking of the purposes and methods of building: it is no longer possible to think of a project without taking into account the safety and well-being of users, energy saving, limiting land use or the choice of innovative materials. [6]

Nowadays, the development of society involves a continuous use of energy and natural resources, and construction is one of the sectors most affected by this issue; for this reason it is important to approach sustainable development in a global way, considering energy improvement, the interaction between the built environment and nature, as well as the phases of the life cycle of our buildings. [7]

In order for an architecture to be considered sustainable in all respects, a responsible design of the entire life cycle of the building is necessary, which considers not only the building in its operational phase (reduction of energy consumption, use of non-toxic materials and attention to polluting emissions), but also in the construction phases and in those phases of disposal of the work at the end of its life cycle, which must take place with the lowest consumption of resources and energy and the least impact on the environment and landscape.

The LCA - Life Cycle Assessment, is a procedure that analyses and quantifies the energy and the environmental loads involved in the construction of a building, taking into account the possible impacts that may arise in a life cycle from the acquisition of raw materials to their disposal.

Two categories of buildings can be distinguished for this scope: new buildings and existing buildings. For new buildings the life cycle consists of:

- production phase: includes the procurement of raw materials;
- construction phase: includes the production of construction materials and their transport;
- usage phase: it groups together the procedures related to the time span of use by users and the actions to keep the building in use throughout its life, for example through operations of renovation and refurbishment;
- End-of-life phase: it essentially considers the management of the waste that will be accumulated during the demolition of the building or, in the case of renovation, the management of the accrued materials.

For the case of existing buildings the scenario is limited to the usage and end-of-life phases.

Often, a product is wrongly defined as ecological only because it is made from recycled material, with the aim of reducing the consumption of raw materials and the production of waste, without considering that a product made from recycled material may have required such a high energy consumption during the reprocessing and transport phases as to totally cancel out or substantially reduce the positive effect of the savings in raw materials; consequently, in order to accurately reconstruct the ecological balance of a product, it is necessary to examine the environmental impacts throughout the entire life cycle, including the production cycle.

The environmental assessment of the life cycle is a method of analysis that evaluates the environmental impacts of a product, a process or a service, through the quantification of material and energy input flows (consumption) and output (emissions) in the phases of extraction of raw materials, transport, production, distribution, use and disposal. This method makes it possible to quantitatively assess the energy and environmental loads caused by a product, process or service throughout its life cycle, "from cradle to grave", a system that considers from the beginning to the end of the life cycle of materials, or "from cradle to cradle", an approach consists of considering materials as capable of regeneration and consequently equating them with natural elements, in the case of recycling.

The elaboration of an LCA study essentially consists of four steps (ISO, 2006):

- definition of the objective and the field of application of the study (Goal and scope Definition);

- inventory analysis ("Inventory Analysis"), of inputs (i.e. inputs such as materials, energy, natural resources) and outputs (i.e. outputs such as emissions to air, water, soil) relevant to the system;
- assessment of both the potential direct and indirect environmental impacts associated with these inputs and outputs (Impact Assessment);
- analysis of the results and evaluation of the improvements of the two previous phases, i.e. the definition of possible courses of action (Interpretation).

The LCA valuation, in particular, takes into account the environmental impacts of the system under study in the area, of ecological quality, of human health and resource depletion; it does not include economic and social considerations.

The method therefore offers many possibilities for use, including:

- identify, quantify, interpret and evaluate the environmental impacts of a product;
- compare the environmental impacts of a product with a reference standard;
- select relevant environmental performance indicators to compare products with the same function;
- identify opportunities for the improvement of the environmental aspects of a product, identifying the stages of the life cycle with the dominant environmental impact;
- assist the decision-making process of industries and public administration;
- communicate environmental information for the presentation of the impacts of a particular intervention.

The users of the LCA tool in the building sector are, on the one hand, designers who, by comparing the environmental impact of different products, can obtain indications to support design choices and have a tool to evaluate the actual eco-compatibility of a product, and, on the other hand, companies which, by identifying the most impacting phases, can adopt strategies to improve the product in terms of eco-efficiency and eco-compatibility.

The limits of the LCA methodology are linked to a series of problems, some of which are also highlighted in the UNI14040:2006 standard:

- the adoption of often subjective assumptions combined with the lack of specific and accurate product rules for individual typologies;
- the limited development of characterisation models that can lead to errors in the transition from the inventory phase to the impact assessment phase;

- the possible errors related to the exclusion of relevant processes from the product system and the absence of some data because they cannot be found in the different databases, including paid ones;
- the limitations of the LCA Interpretation phase regarding the quality of the data used, which may be missing some input and output streams or present different allocation criteria;
- the lack of a clear spatial and temporal definition of impacts that does not allow for accurate analyses especially in cases of impact categories that have effects on a local or regional scale.

The information developed through an LCA evaluation should be used as part of a more comprehensive decision-making process that also includes cost and performance, such as Life Cycle Costing, a methodology that allows costs to be assessed over the entire life cycle of a product, from production to disposal. "Life cycle" means that LCC assesses all costs that occur during the life of the building, including construction, maintenance, operation and end-of-life costs.

Therefore, the costs that should generally be included in such an analysis are:

- purchase and installation;
- costs during the usage and the maintenance phase;
- disposal costs;

The concept can be schematised as follows:

LCC = Purchase cost + Maintenance and repair cost + Water consumption + Energy consumption + Replacement cost - residual value + Disposal cost. [2]

Sustainable design is a solution that in recent years has found more and more space and consensus; if in ancient times the "km0" construction made use of local raw materials, of natural origin, today these "km0 raw materials" could be sought in the tons of waste materials coming from construction and demolition through the introduction of recycled materials with innovative solutions.

Recently, an interesting alternative has been reported: the development of alternative binders with low CO2 emissions (alkali-activated materials, geopolymers and calcium sulphur aluminate cements) [8, 9]. Geopolymers are obtained through a chemical reaction of a starting alumina-silicate powder with a highly concentrated aqueous solution of hydroxide and/or alkali silicate producing a new amorphous-semicrystalline alumina-silicate synthetic phase [10-12]. Alkali-activated materials (AAM) show excellent properties in terms of mechanical performance [13], thermal stability [14] and durability [15].

Moreover, they are of great interest for their high sustainability also due to the reduced energy demand for their production. In fact, the production of geopolymers allows an 80% reduction of emissions compared to the production of Portland cement [10]. It has been shown that any natural or synthetic material containing an adequate amount of silica and alumina can be used as a precursor for the geopolymerisation process [11].

1.2. Environmental impact of the construction industry

The construction industry occupies an important position in the production of waste materials; about 1/3 of the total waste in the European Union is Construction and Demolition Waste (CDW), which is material resulting from construction and demolition activities. The materials produced range from plastics to wood, metals and inert materials. For this reason, the EU has considered the CDW stream as a priority stream for its actions. In fact, in the last decade, the intense activity in the field of construction generated in Europe about 827 million tonnes of CDW on average per year and yet only 50% of this CDW was recycled [16, 17].

The initial tendency of dealing with recycling in terms of recovery of large amounts of waste, without added value, has in the following years turned into a greater focus on innovative reuse of waste, which is increasingly moving in the direction of the circular economy; this type of approach leads as a consequence to a lower environmental impact. Ceramics, for example, is one of the products that generate the greatest environmental impact from the moment it is manufactured to its disposal. In fact, in Mediterranean countries such as Spain or Italy, waste from ceramic products such as bricks or tiles, for example, represents about 54% of the construction and demolition waste (CDW) produced [18].

To support the transition to a Circular Economy, hydraulic "cocciopesto" mortars can now be produced using ceramic industrial waste [19] or indeed the brick, tile, cladding and brick fraction of demolition waste [20] in accordance with recent European and national directives. However, the tendency to reuse all waste, scrap and spoil materials is certainly not a recent invention; there are many examples coming from antiquity. Without going back too far to the times of the Ancient Romans, this type of activity can also be found, for example, among the construction techniques of our region Campania, where the absolute practicality of using unhewn stone or unfinished wooden beams led to a saving in terms of time in carrying out the operations and also a saving in terms of cost, being able to employ a non-specialised workforce, with the use of all the material available on site, and often re-using the material resulting from demolitions and collapses, whether occurring naturally or not. This approach, although it is based on purely practical aims, is perfectly coherent with the criteria that nowadays are trying to be brought back into the construction industry. [21]

1.3. C&D waste

The category of inert materials is the one with the highest percentage of weight, reaching 75-80% of the total [22, 23]. About 45% of construction and demolition waste (CDW), on the other hand, is attributed to ceramic products such as bricks, tiles and porcelain.

The materials resulting from construction and demolition activities are classified through a specific list: the "European Waste Code" (CER) introduced by Directive 75/442/CEE. The codes consist of a sequence of 3 pairs of numbers, which identify the waste according to its production process. Class 17 of the European Waste List covers waste produced by construction and demolition operations (including soil from contaminated sites) and contains:

- **17 01 00 concrete, bricks, tiles and ceramics**
  17 01 01 concrete
  17 01 02 bricks
  17 01 03 tiles and ceramics
  17 01 06* mixtures or drosses of cement, bricks, tiles and ceramics containing dangerous substances
  17 01 07 mixtures or drosses of cement, bricks, tiles and ceramics other than those mentioned in 17 01 06

- **17 02 00 wood, glass and plastic**
  17 02 01 wood
  17 02 02 glass
  17 02 03 plastic
  17 02 04* glass, plastic and wood containing or contaminated by dangerous substances

- **17 03 00 bituminous mixtures, carbon tar and tar-containing products**
  17 03 01* bituminous mixtures containing carbon tar
  17 03 02 bituminous mixtures other than those mentioned in 17 03 01
  17 03 03* carbon tar and tar-containing products

- **17 04 00 metals (including their alloys)**
  17 04 01 copper, bronze, brass

17 04 02 aluminium
17 04 03 lead
17 04 04 zinc
17 04 05 iron and steel
17 04 06 tin
17 04 07 mixed metals
17 04 09* metal waste contaminated with dangerous substances
17 04 10* cables containing oil, coal tar and other dangerous substances
17 04 11 cables other than those mentioned in 17 04 10

- **17 05 00 soil (including soil from contaminated sites), rocks and dredging sludge**
  17 05 03* soil and stones containing dangerous substances
  17 05 04 soil and stones other than those mentioned in 17 05 03
  17 05 05* dredging spoil containing dangerous substances
  17 05 06 dredging spoil other than those mentioned in 17 05 05
  17 05 07* rail embankment gravel containing dangerous substances
  17 05 08 rail embankment gravel other than those mentioned in 17 05 07

- **17 06 00 insulation and building materials containing asbestos**
  17 06 01* insulation materials containing asbestos
  17 06 03* other insulation materials containing or consisting of dangerous substances
  17 06 04 insulation materials other than those mentioned in 17 06 01 and 17 06 03
  17 06 05* construction materials containing asbestos

- **17 08 00 gypsum-based construction materials**
  17 08 01* gypsum-based construction materials contaminated with dangerous substances
  17 08 02 gypsum-based construction materials other than those mentioned in 17 08 01

- **17 09 00 other construction and demolition waste**
  17 09 01* construction and demolition wastes containing mercury
  17 09 02* construction and demolition wastes containing PCB (e.g. PCB-containing sealants, PCB-containing resin-based floorings, PCB-containing sealed glass units, PCB-containing capacitors)

17 09 03* other construction and demolition wastes (including mixed wastes) containing dangerous substances

17 09 04 mixed construction and demolition wastes other than those mentioned in 17 09 01, 17 09 02 and 17 09 03

1.4. Partial conclusion of the chapter

In the last decade a growing interest in so-called construction and demolition waste has taken place. For several years great efforts have been devoted to their recovery, especially from a quantitative point of view, without considering innovative recovery in terms of quality and performance. Today, however, research is increasingly focusing on solutions aimed at circular design and construction, thinking about closing the production circle by the upcycling of waste. If it is true that the usage phase of the building still represents the most significant item of the life cycle, both in terms of resources consumption and emissions, the reduction of impacts linked to the final phase, through adequate strategies of reuse, recycling and recovery of materials, can assume a strategic importance not only in terms of reduction of the corresponding emissions [24], but also through a reduction of resources consumption due to the extraction of raw materials and the production of materials [25]. The transition to sustainable construction is no longer a choice, but a necessity to improve the quality of life of citizens, to reduce energy consumption, to give more value to the houses, to reduce emissions and the energy dependence of our country. The choice of one product or another, or of a building system, is closely related to the evaluation of a series of external factors, which entail the need to analyse the most appropriate solution during the design phase, which will always be different from case to case.

What has yet to really happen is a re-founding of the principles of architecture to respond to environmental problems that it is now impossible to ignore. Unfortunately, architecture does not have immediate answers and fully reflects the complexity of the transformation of cultural processes, which require time and conviction to absorb new approaches.

In any case, disseminating information and raising awareness not only among designers but among all citizens on the issue of sustainability is a step forward every day, not only towards the well-being of our planet, but also towards a better quality of life. [2]

The possibility of including CDWs in building materials is an interesting alternative. Climate changes and environmental problems, combined with and linked to industrial activities, are a wake-up call for the depletion of resources due mainly to the exploitation of raw materials. In this sense, the amount of used material coming from construction and demolition operations represents a very valuable asset. For this reason, there is an urgent need to evaluate alternative applications of this waste considering the large quantities produced per year (annual production in the EU is estimated at 855 million tonnes) [26].

According to previous studies on new materials made with circular economy criteria [27-33] there are interesting possibilities to recycle these materials by transforming them into recycled aggregates, which can be used as raw materials.

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CHAPTER 2 Objectives of the proposed research

The aim of this research work has been, from the very beginning, the identification of a sustainable answer to the problem of construction and demolition waste management; a sustainability intended not only from an environmental point of view, but also an economic and a social one. From a careful analysis of the literature, from a direct comparison with representatives of the scientific community and from the acquisition of data compared to what is currently available on the international scene, it emerged that the use of recycled materials is hindered by bureaucratic, technical and social aspects. From a technical and bureaucratic point of view, it is not only about the recycling of waste materials, but also and above all about producing materials that meet the performance limits and the quality characteristics required by the regulations; this aspect, together with a lack of information and training, is a determining factor in the choice of these resources, which are viewed with distrust by both companies and technicians who are unable to perceive the potential of products that are only considered "second-hand", hence the social limitation. In order to ensure that what is currently considered waste acquires its true value, it is therefore essential to consider all the factors involved at the same time. But what leads to the production of all this material for reuse?

There are essentially three aspects to consider:

- naturals: following major disasters and catastrophes, much of the material is already in the form of rubble, and the remainder of the buildings must be demolished in order to proceed with any reconstruction;
- legislative: often, especially in our territory, indiscriminate building has taken place without taking into account the provisions of the law, and we are therefore dealing with a vast panorama of unauthorised buildings, whether total or partial, which must be demolished to restore the state of the places;
- technical: the techniques used are often inadequate, from the point of view of the security, of the environment and of the functions; modern society imposes changes, the needs change, the environmental conditions change, the technical knowledge changes, and so the constructions find themselves to no longer respond to the standards that are gradually changing; for example, security from the point of view of seismic or fire safety, or from the point of view of the lack of maintenance and the consequent deterioration of the building elements, which has led to sadly notorious consequences, the aspect of energy and environmental standards and the failure to meet the functional requirements of everyday life.

The immediate resolution to the construction elements in order to satisfy the natural and technical aspects is the renovation. But when it is not possible to recover the building, how can we recover its materials in a sustainable way?

This international research work through the synergy between chemistry and technology focuses not only on the application of these materials in new projects, but also in the recovery of existing buildings; in this sense there is a need to reintroduce these "new secondary materials at km0" such that they are compatible not only from a formal and technological point of view but also from a material point of view. Therefore, starting from environmental, economic and social analyses of the impossibilities of building recovery, the aim is to investigate the possibilities of recovering building materials in a sustainable way, in the production of prefabricated building components by means of alkaline activation with sodium hydroxide and silicate solution. The purely applicative part of the research focused on the production of samples starting with the choice of waste materials such as tuff, concrete and brick, determining the performance composition and, ultimately, evaluating the properties of the different samples with the aim of creating new environmentally sustainable materials to be introduced into the building construction market.

Main objective: the development of new sustainable geopolymer-based building materials using demolition waste.

Specific objectives:

- analysis of the state of the art related to previous applications;
- selection of construction and demolition residues and analysis of their geopolymerisation capacity;
- analysis of the developed geopolymers by chemical and physical characterisation;
- proposal of applications in the construction field based on the characteristics found.

CHAPTER 3 Stat of the art

From the study carried out and proposed below, it emerges that, despite the advantages of recovering building rubble, there are still many uncertainties and obstacles, especially of a bureaucratic nature, that hinder its development. Although much attention is being paid to good practice in future planning with the aim of having easily reusable materials, we should not forget how much has already been achieved and how many potentially secondary raw materials are already in existence.

Before proceeding to an analysis of what has been done so far in Italy and in Europe, it is useful to focus on some legal provisions in order to highlight the objectives and the bureaucratic aspects that govern the world of waste coming from construction and demolition activities. What emerges and is reported below is that surplus recovery operations, if they comply with certain quality standards, result in the production of secondary raw materials, thus enhancing the value of materials otherwise seen simply as waste. In particular, Article 7 of Legislative Decree no. 205 of 3 December 2010 - Provisions implementing Directive 2008/98/CE of the European Parliament and of the Council of 19 November 2008 on waste - amended Article 181 of Legislative Decree no. 152/2006, specifying that *"by 2020 the preparation for re-use, recycling and other material recovery, including backfilling operations using waste as a substitute for other materials, of non-dangerous construction and demolition waste, excluding material in the natural state as defined in waste entry 17 05 04, shall be increased to at least 70 per cent by weight", and in Article 182, regarding disposal, adds:*

"1. Waste disposal is carried out under safe conditions and is the residual phase of waste management, after verification by the competent authority that it is technically and economically impossible to carry out the recovery operations referred to in article 181. To this end, such verification shall concern the availability of techniques developed on a scale which allows their application in economically and technically viable conditions within the relevant industrial sector, taking into consideration the costs and advantages, whether or not they are applied or produced domestically, as long as they are reasonably accessible.

2. Waste for final disposal shall be reduced as far as possible, both in mass and in volume, by increasing prevention and reuse activities, by promoting recycling and recovery, and by giving priority, where practicable, to non-recoverable waste generated in recycling or recovery activities"; thus emphasising the need to preferentially pursue recovery and reuse.

It is therefore important to understand how and under what conditions, the waste material is transformed into a by-product, i.e. the result of a production process; in *article 184 ter. we see precisely that "A waste ceases to be a waste when it has undergone a recovery operation, including recycling and preparation for re-use, and meets the specific criteria, to be adopted in compliance with the following conditions:*

(a) the substance or object is commonly used for specific purposes;

(b) a market or demand exists for that substance or object;

(c) the substance or object meets the technical requirements for the specific purposes and complies with existing legislation and standards applicable to products;

(d) the use of the substance or object will not lead to overall adverse environmental or human health impacts."

The decree also sets out all the bureaucratic operations to be carried out by the future managers of the plants, the practices and timeframes, and all the information to be provided for the start of recovery and disposal activities, including the R13 storage of waste, which is intended as a storage activity for subsequent treatment at recovery or disposal plants. It is important to specify that if waste is temporarily deposited at the place of production, it does not fall into the case of putting it in reserve, this temporary storage lasts three months and once this period has elapsed it is obligatory to start disposal. This transposing Legislative Decree provides that these criteria are defined by implementing Decrees approved by the Ministries of the Environment and Economic Development (Art.6 of Legislative Decree 205/2010).

Article 178 of Legislative Decree 152/2006 - Environmental Code - "Environmental regulations" in Part Four - Waste Management, as amended by No. 205 of 2010, further specifies that *"waste management is carried out in accordance with the principles of precaution, prevention, sustainability, proportionality, accountability and cooperation of all parties involved in the production, distribution, use and consumption of goods from which waste originates, as well as the polluter pays principle. For this purpose, waste management shall be carried out according to criteria of effectiveness, efficiency, cost-effectiveness, transparency, technical and economic feasibility, as well as in compliance with the rules in force on participation and access to environmental information*" [33] and adds in the following article that "waste management shall take place in accordance with the following hierarchy:

(a) prevention;

(b) preparation for re-use;

(c) recycling;

(d) other types of recovery, e.g. energy recovery;

(e) disposal.

And in paragraph 2 *"The hierarchy establishes, in general, an order of priority of what constitutes the best environmental option...measures shall be taken to encourage those options which guarantee...the best overall result, taking into account health, social and economic impacts, including technical feasibility and economic viability...".* It also provides, in art. 183, all the definitions in detail, among others we find the one of "waste", "dangerous waste", "recovery", "temporary storage" defined as: "the grouping of waste and the storage prior to collection for the purpose of transporting such waste to a treatment plant, carried out, prior to collection, in the place where the waste is produced, to be considered as the entire area in which the activity that determined the production of the waste takes place" and in particular it specifies the modalities of collection and delivery to the landfill according to two types of modalities: o *at least every three months, regardless of the quantity of waste in storage, or when the quantity of waste in storage reaches a total of thirty cubic metres, including a maximum of ten cubic metres of dangerous waste. In any case, when the quantity of waste does not exceed the aforementioned limit per year, temporary storage cannot last more than one year"*, and classifies waste into urban, special and dangerous waste; in particular, it defines as special the waste deriving from demolition and construction activities, as well as the waste deriving from excavation activities; and adds to art. 184 ter that “" *A waste ceases to be a waste when it has undergone a recovery operation, including recycling and preparation for re-use, and complies with specific criteria, to be adopted in accordance with the following conditions:*

(a) the substance or object is commonly used for specific purposes;

(b) a market or demand exists for that substance or object

(c) the substance or object meets the technical requirements for the specific purposes and complies with existing legislation and standards applicable to products

(d) the use of the substance or object will not lead to overall adverse environmental or human health impacts.”

With regard to the Directive 2008/98/CE [34] of the European Parliament on waste, it can be said that it advances a hierarchical waste management that prefers prevention to production, preparation for re-use and then recycling or other types of recovery. Disposal in landfills is the last viable option in order to reduce the overall impact of resource use while protecting human health and the environment, furthermore in article 3 the preparation for re-use and recycling is defined as:

- *«preparing for re-use» means checking, cleaning and repairing operations by which products or components of products that have become waste are prepared so that they can be re-used without any other pre-processing;*
- *«recycling» means any recovery operation by which waste materials are reprocessed in order to obtain products, materials or substances to be used for their original function or for other purposes. It includes the reprocessing of organic material but not the energy recovery nor the reprocessing to obtain materials to be used as fuels or in backfilling operations.*

Finally of great relevance, with the new Codice degli Appalti (Legislative Decree 50/2016) is the mandatory application of CAM, Minimum Environmental Criteria, to ensure the best design solution from an environmental point of view, to date the adopted CAMs affect seventeen categories, with regard to construction, it specifies that: *"Projects for new construction activities, including demolition and reconstruction interventions, shall include a plan for the selective disassembly and demolition of the work at the end of its life that allows for the reuse or recycling of the materials, building components and prefabricated elements used... the designer shall present a plan for the "end of life" phase of the building listing all materials, building components and prefabricated elements that can be subsequently reused or recycled, with an indication of their weight in relation to the total weight of the building. "* It also states that *"The content of recovered or recycled material in the materials used for the building shall be at least 15% by weight assessed on the total of all materials used. Of this percentage, at least 5% must be made up of non-structural materials... In order to reduce the use of non-renewable resources, reduce waste production and landfill, with particular regard to demolition and construction waste (in accordance with the target of recovering and recycling at least 70% of not dangerous construction and demolition waste by 2020), the project must provide for the use of materials produced with a certain recycled content..."* this percentage, for concrete and precast concrete elements must be at least 5% by weight of the product (intended as the sum of the individual components) and/or with recovered materials, and/or by-products. For bricks used for masonry and floors the percentage must be at least 10% by weight of the product *"if the bricks contain, in addition to recycled and/or recovered materials, also by-products and/or excavated soil and rocks, the percentage must be at least 15% by weight of the product".* In the case of bricks for roofs, floors and fair-faced masonry, the content of recycled and/or recovered materials (on a dry weight basis) is expected to be at least 5% "*if the bricks contain, in addition to recycled and/or recovered materials, also by-products and/or excavated soil and rocks, the percentage must be at least 7.5% by weight of the product*". The paragraph concerning iron, steel and cast iron reports the following minimum contents: "*for structural uses, steel produced with a minimum content of recycled material must be used, as specified below according to the type of industrial process: electric furnace steel: minimum content of recycled material equal to 70%, full cycle steel: minimum content of recycled material equal to 10%*". This percentage rises to 30% by weight assessed on the total of all components for the plastic materials used, while 5% is considered for partitions and false ceilings intended for drywall systems. Finally, with regard to masonry for foundation and elevation works, the use of only recycled material (stones and blocks) is prescribed.

Furthermore, in 2018, the European Parliament gave final approval to the regulatory package on the Circular Economy (which includes Directive 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/CE on waste) which sets new and more ambitious targets concerning preparation for reuse and recycling of waste. In Italy, on 7 August 2020, the Council of Ministers definitively approved the four legislative decrees transposing the same four EU directives on waste that are part of the above-mentioned regulatory package. Moreover, already on 2 February 2016, with the 2016 Stability Law, the Collegato Ambientale (Law No. 221 of 28 December 2015) had come into effect, containing provisions on environmental legislation aimed at promoting the green economy and sustainable development, which allowed the principles of the circular economy to become part of the Italian legal system. Also in 2016, the Ministry of the Environment had issued a decree (Ministerial Decree No. 264 of 13 October 2016) introducing the "Regulation containing indicative criteria to facilitate the demonstration of the existence of the requirements for the qualification of production residues as by-products and not as waste".

3.1. C&D Waste management

In Italy in the year 2016, the production of special waste stood at almost 135.1 million tonnes of which almost 53.5 million tonnes came from construction and demolition activities. "The estimated share of non-hazardous waste produced represents 46.1% of the total figure, mainly due to the significant contribution of waste generated by construction and demolition activities" [35] about 43%; not forgetting the percentage of waste from construction and demolition operations performed abroad and imported into Italy for recovery/disposal operations that in year 2016 was equal to 2.4 million tonnes and the percentage of those exported from Italy equal to about 89 thousand tonnes.

Also from the ISPRA Waste Report 2018, in relation to the two-year period 2015-2016, a 1% increase in the production of waste from C&D activities emerges, compared to 5.5% in the previous two-year period. The production, in fact, is around the following figures: 50,214,864 t/a in 2014, 52,978,023 t/a in 2015 and in the 2016 53,492,199 t/a.

Tabella 1.4 – Fattori utilizzati per il calcolo della variazione percentuale del rapporto RS non pericolosi da C&D/PIL di settore, anni 2011 - 2016

Variazione RS non pericolosi da costruzione e demolizione/PIL				
Anno	PIL a prezzi correnti - settore delle costruzioni (milioni di Euro)	RS non pericolosi da costruzione e demolizione (tonnellate)	RS non pericolosi da costruzione e demolizione/PIL settore delle costruzioni (t/milioni di Euro)	Δ (RS non pericolosi da costruzione e demolizione/PIL settore delle costruzioni)$_{2010,2010+n}$ (%)
2010	81.207	57.421.288	707	
2011	76.979	58.079.423	754	6,70%
2012	71.649	51.629.208	721	1,91%
2013	68.017	47.939.874	705	-0,32%
2014	64.171	50.214.864	783	10,67%
2015	63.643	52.978.023	832	17,72%
2016	63.683	53.492.199	840	18,79%

Fonte: ISPRA; dati degli indicatori socio economici utilizzati nelle elaborazioni:ISTAT

Figure n.1 – C&D waste table. Source ISPRA Waste Report 2018

In particular, the production of waste from C&D operations is increasing (+2.2% compared to 2015) in the North, by +3.7%, over 483 thousand tonnes, in the Centre while in the South there is a decrease of -2.7%.

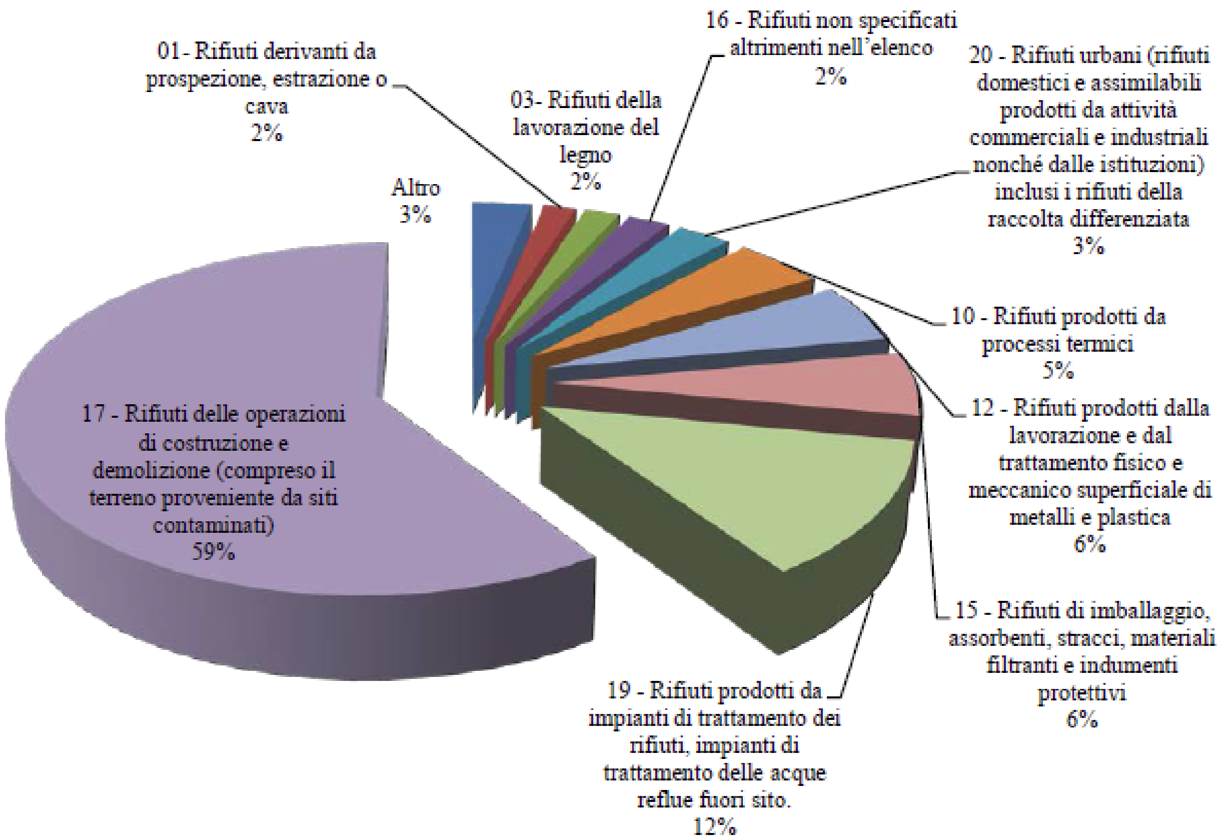
Tabella 1.8 – Produzione dei rifiuti speciali per macroarea geografica, anni 2015 – 2016

Tipologia rifiuto	Nord		Centro		Sud		Italia	
	2015	2016	2015	2016	2015	2016	2015	2016
RS NP (MUD)*	37.048.846	37.525.294	12.981.215	13.464.490	16.090.888	16.628.567	66.120.949	67.618.351
RS NP esclusi i rifiuti da C&D (stime)	2.402.842	2.483.231	720.915	739.769	1.096.635	1.137.822	4.220.392	4.360.822
RS non pericolosi da C&D (stime)	30.561.056	31.241.543	9.604.846	9.781.857	12.812.121	12.468.799	52.978.023	53.492.199

Figure n.2 - C&D waste tables 2015-2016. Source ISPRA Waste Report 2018

With regards to waste management: "In the North, the highest production values of special construction and demolition waste are found for the region of Lombardy (almost 12 million tonnes), which covers 38.4% of the total production of construction and demolition waste in the macro geographical area under review, equal to about 31.2 million tonnes; it is followed by Veneto (over 5.1 million tonnes, 16.5%), Emilia Romagna (almost 5 million tonnes, 15.8%) and Piedmont (about 4.5 million tonnes, 14.5%). In the Centre of Italy, Tuscany produces more than 4.2 million tonnes of construction and demolition waste, equivalent to 43.2% of the total produced in the macro area (almost 9.8 million tonnes), and Lazio about 3.7 million tonnes (37.6% of the total of the macro area). Finally, in the South, where the total production of construction and demolition waste reaches almost 12.5 million tons, the regions that produce the most significant quantities are Puglia, with 3.5 million tons (28.1% of the total of the macro area), Sicily (over 2.9 million tons, 23.4%) and Campania (almost 2.9 million tons, 23.1%)". It should also be said that dangerous C&D waste in the two-year period 2015-2016 increased by about 50 thousand tonnes (+6.4%), mainly due to soils and rocks while the percentage of waste containing asbestos and mixed waste from construction and demolition activities decreased by about 13 thousand tonnes.

Considering recovery and disposal operations, we can see that in 2016 59% of the non-hazardous waste destined for recovery came from C&D activities, while 11% of that intended for disposal.



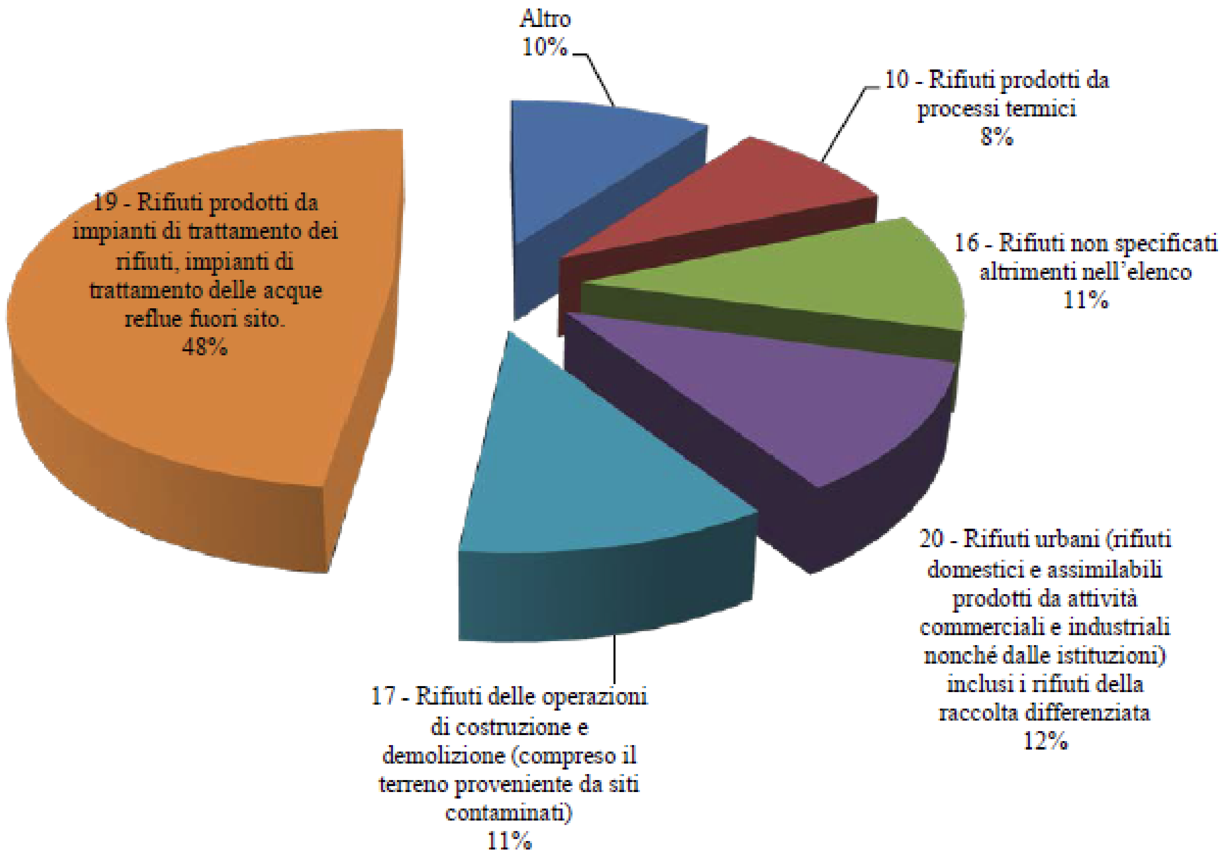
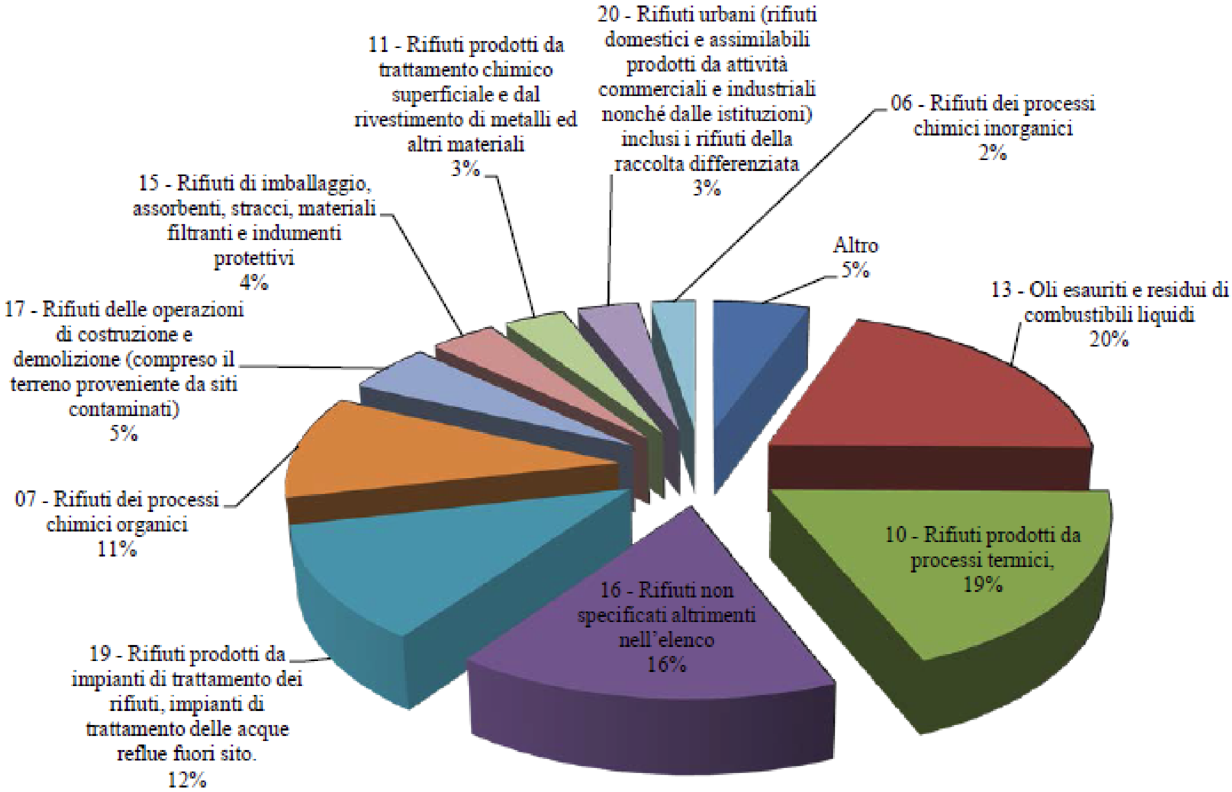


Figure n.3 - Percentage of non-hazardous waste recovered and disposed of in 2016. Source ISPRA Waste Report 2018



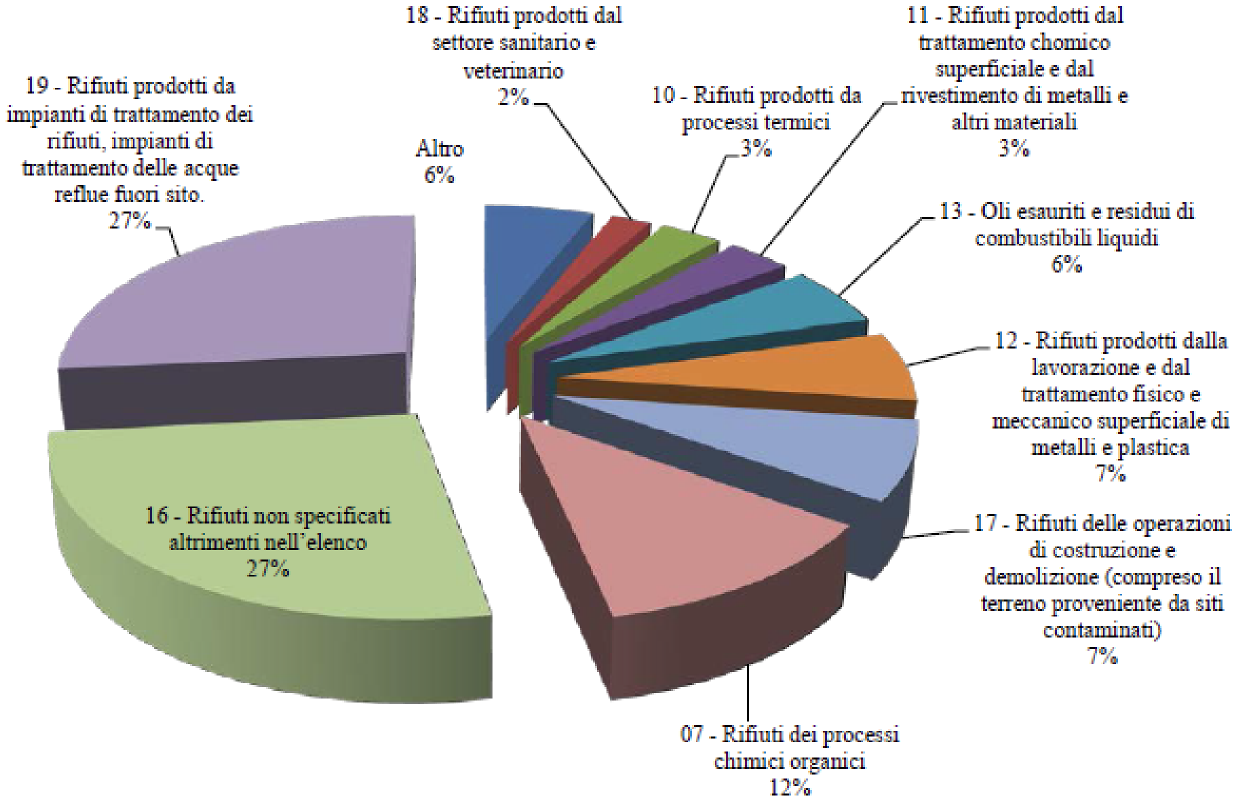


Figure n.4 - Percentage of hazardous waste recovered and disposed of in 2016. Source ISPRA Waste Report 2018

Data recorded on the amount of C&D waste disposed of in 2016 show an increase of 1.2% compared with the previous year. Most of the non-hazardous C&D waste was made up of excavated soil and rocks (71%), while 16.2% was composed of mixed construction and demolition waste and the remaining 12.8% (around 327 thousand tonnes) of other types of waste.

Concerning dangerous waste, the 68% (231 thousand tonnes) of this is related to waste containing asbestos, while 17.6% is related to other insulation materials and the remaining 14.4% (about 49 thousand tonnes) to other types of dangerous waste. More than half of this is disposed of in plants located in Northern Italy. With regard to special waste disposal plants, there was a decrease in units from 2014 to 2016, from a total of 392 plants to 350 ones.

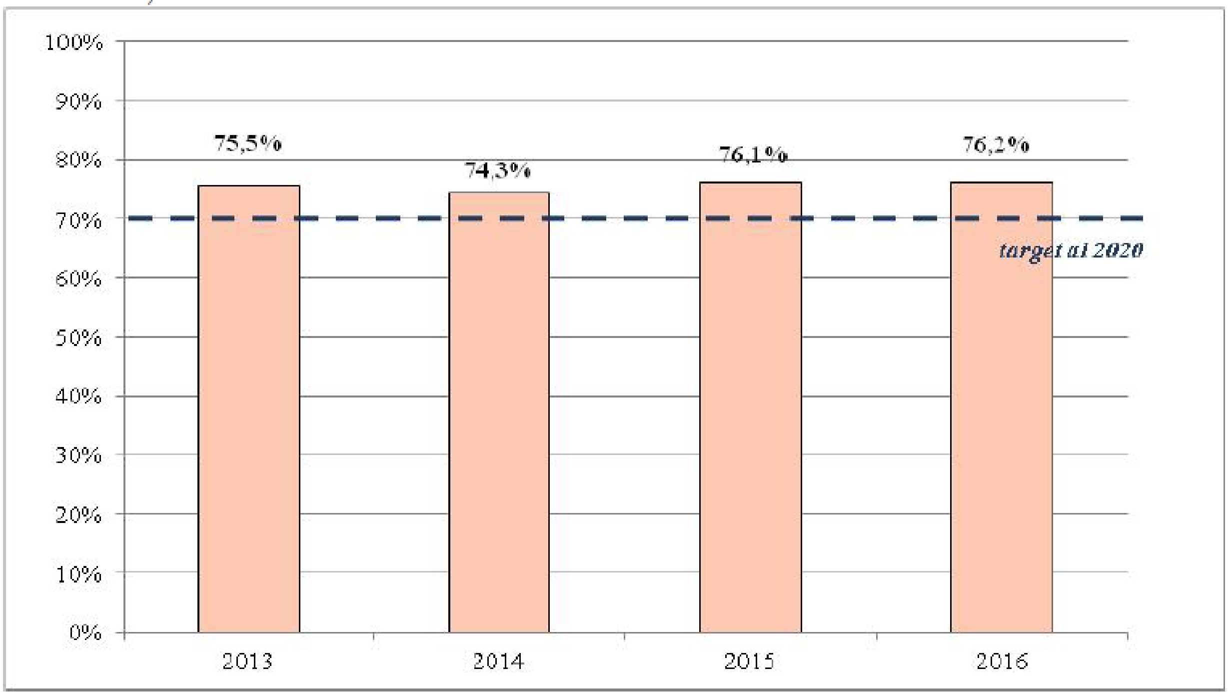
Despite the increases recorded, according to the ISPRA Waste Report 2018, the percentage set at 70% in 2016 is exceeded, as shown in the following tables:

Tabella 4.5.3 - Tasso di recupero di materia dei rifiuti da costruzioni e demolizioni, anni 2013 - 2016

2013	2014	2015	2016
75,5%	74,3%	76,1%	76,2%

Fonte: ISPRA

Figura 4.5.1 – Andamento della percentuale di preparazione per il riutilizzo, riciclaggio e delle altre forme di recupero di materia, escluso il *backfilling*, dei rifiuti da costruzioni e demolizioni, anni 2013 – 2016



Fonte: ISPRA

Figure n.5 - Percentage of recovery. Source ISPRA Waste Report 2018

However, this information must be evaluated with a certain degree of uncertainty due to the fact that the data collection is not exhaustive and is determined by the percentage of undeclared or illegally managed waste.

It is important to underline, therefore, that in Italy, when we talk about building rubble, we talk first of all about waste, considered as "any substance or object which the holder discards or intends or is obliged to discard", as reported in art. 183 of the Legislative Decree 152/2006, without the possibility, consequently, of transforming it into a by-product, defined instead as "those substances or objects whose destination for reuse in the same production cycle or reuse by third parties is certain from the beginning and not potential. In order to meet the increasing need to recover these materials and at the same time avoid the creation of an illegal landfill by stacking the waste waiting for a possible future reuse, a judgment of the Court of Cassation (n.41607 of 13 September 2017) has established that the materials resulting from the demolition of a building can be considered as by-products only if the intention to reuse them is explicitly stated in advance through an environmental permit for the recovery of inert materials. [36]

3.2. C&D waste recovery: projects and actions undertaken

The concept of recovery is a practice already known in the past: in Roman times, the concept of recycling was most widespread in times of deep economic crisis or shortage of raw materials; in periods when resources were scarce following catastrophic events such as earthquakes, floods or fires, most waste was recycled and many buildings were constructed using products obtained from previous works. The fundamental rule was the use of all available material: the preference was to crush the stones and rework the quarry blocks directly on the building site to obtain masonry stone; the slag was used in small-scale reclamation or recycled in the preparation of cement floors and wall plaster. The reuse and processing of brickwork was also important. Furnace rejects and defective ceramics were often used as light filler in vaults, while fractured tiles were frequently used in foundations or mixed masonry. The waste resulting from the cutting of bricks was normally used in the composition of hydraulic mortars and cocciopesto. The recycling of glass waste by remelting was also a widespread practice in the Roman world, for both economic and practical reasons; starting from a semi-finished product, it shortened the normal manufacturing process.

In the pre-industrial era in Great Britain, ashes from wood fires and carbon were collected and reused as base material in the production of bricks.

But what strongly encouraged recycling was the shortage of resources caused by the world war. Massive promotion campaigns were carried out in all the countries involved, inviting citizens to donate metal materials as a sign of love for their country.

European environmental policy developed considerably from the 1970s onwards, helping to improve air and water quality and highlighting the importance of a healthy environment for humans.

In 1973-1975, the oil crisis raised awareness of the finite and exhaustible nature of natural resources.

In 1983, the United Nations set up the Bruntland Commission, that is the World Commission on Environment and Development, which published a report in 1987, entitled "Our Common Future", in which it focused on environmental protection as an indispensable element for an adequate development of society also from an economic and social point of view.

Then in 1992, the United Nations Conference on Environment and Development (UNCED) was held in Rio de Janeiro, where topics such as alternative energy resources, reduction of harmful emissions, limitation of toxin production, climate change and biodiversity were discussed. The Conference approved several documents, including the Rio Declaration and Agenda 21, which are fundamental references for policies and initiatives aimed at sustainable development in the 21st century.

In 1997, the Kyoto Protocol was approved, providing for a reduction of at least 5% in emissions of gases such as CO_2, greenhouse gases, methane and nitrogen oxide by industrialised countries compared to emissions in 1990.

It is therefore from the end of the 1990s that a new perspective towards a development "aimed at meeting the needs of the present without compromising the ability of future generations to meet their own needs" began to emerge.

Between 2005 and 2006, as we have seen, the European Commission proposes seven thematic strategies that form an integral part of the new approach to environmental policy-making. This is the sixth 10-year environmental action programme, which will create a distinct vision of human impact on the environment and begin a journey towards a desire for improvement in the environmental and energy fields. It is a revolution in environmental terms, initially taking place in 2006 with Directive 2006/12/CE and finally being amended in 2008 (Directive 2008/98/CE). The Thematic Strategy on the prevention and recycling of waste, adopted by the European Commission, is based on the Sixth Environmental Action Programme and was accompanied by a detailed impact assessment and a legislative proposal aimed at amending and consolidating the European Union's framework legislation on waste.

This strategy was followed by the introduction of the Seventh Environment Action Programme, which is structured in a more detailed and specific form than the themes already discussed and provides a more focused overview of the recycling issue. The Seventh Environment Action Programme sets out the challenges to be met, the targets to be achieved and defines a European planning framework for the environment for the next decade. It is based on innovative principles in the environmental sector, such as the principle of preventive action and reducing pollution at its source.

On the subject of recycling, in Italy, a directive was drawn up in 2006 that steers towards a path of respect for resources and the conscious use of materials. It took its fullest form with the 2008 amendment (Directive 2008/98/CE) in which the theme of recycling takes on its own form and its own application methodology thanks to new practices for waste disposal. To achieve the targets, practices, fields of application and guidance on how to minimise waste are described. A waste hierarchy for waste prevention and management is established, as well as a waste type classification for greater awareness of which administrative practice to implement. This differentiation is aimed at reducing waste in terms of raw materials, using all possible actions, including recovery (art. 10), re-use and recycling (art. 11).

Italian legislation bases its knowledge of recycling on European directives and has drawn up a legislative decree (Legislative Decree 152/06), later amended in 2010 (Legislative Decree 205/10), divided into several chapters, each referring to a specific subject:

- Soil and water protection
- Waste management and reclamation of polluted sites
- Protection of air and emissions
- Protection and compensation for environmental damage

In the new legislative decree the definition of waste, although it is not substantially different from the previous one, has been better circumscribed through the inclusion of specific rules for by-products, which are not waste, and for secondary raw materials.

Looking at the European directive, the Italian legislation offers a more detailed classification of waste and, consequently, a greater description of the disposal and management practices for each individual category. The latter differs from the European one in that it provides a more precise specification of each element and product - recyclable - or for landfill, in order to achieve the highest possible material optimisation.

In 2012, the United Nations Conference on Sustainable Development, Rio+20, assesses the progress achieved, the remaining gaps and the political commitment to sustainable development. For the first time, it talks about a green economy based on sustainable waste management through the application of the 3Rs: Reduce, Reuse and Recycle.

Among the main objectives:

- give the planet's resources time to regenerate;
- minimise energy consumption;
- produce energy using renewable sources;
- minimising waste emissions into the environment through policies that encourage reuse and recycling;
- identifying industrial processes that have less impact from the point of view of the emissions released;
- adopting environmental compensation policies by promoting zero impact actions [37].

The European Commission, as we have said, has also set the goal of reducing environmental impact and safeguarding resources, and has identified construction and demolition waste as a priority stream because of the huge quantities generated, amounting to around 374 million tonnes in the EU-28 in 2016 according to the European Environment Agency. The target of 70% recovery of materials from C&D operations by 2020, set out in Article 11 of Directive 2008/98/CE of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, although exceeded by many countries already in 2016, has highlighted significant criticalities related to the prevalence of low quality recovery.

The achievement of European objectives, which requires a high investment in innovation, cannot disregard the effectiveness of the financial instruments put in action. In the next European programming period (2021-2027), the LIFE programme, which has been promoting projects aimed at environmental protection since 1992, will be the only fund dedicated to the environment and climate, and one of its priority objectives is to encourage the transition to a circular economy that is energy efficient, based on renewable energy, climate neutral and resilient.

3.2.1. The European Life Programme

The LIFE programme is a 'Financial Instrument for the Environment' dedicated to promoting projects aimed at protecting the environment through the conservation of resources and the development of new methods. *“LIFE's overall objective is to contribute to the implementation, updating and development of EU environmental and climate policy and legislation by co-financing projects with European added value.”*[38]

The LIFE project started in 1992 and has seen the complete development of 4 phases: LIFE I (1992-1995), LIFE II (1996 - 1999) LIFE III (2000-2006) and LIFE + (2007-2013). After these phases, Regulation (CE) No 1293/2013 LIFE 2014-2020 was published in order to contribute to sustainable development and to the achievement of the Europe 2020 objectives. This regulation established the sub-programmes for the financial period 2014-2020 and set a budget of EUR 3.4 billion, at the end of the mid-term evaluation of LIFE 2017 it gave a very positive feedback for the first four years, for this reason in November 2017 was adopted by the Commission, the multiannual work programme LIFE 2018-2020 which identifies seven priority areas of intervention:

- Environment and resource efficiency;
- Nature and biodiversity;
- Environmental governance;
- European Solidarity Corps;
- Climate change mitigation;
- Climate change adaptation;
- Climate governance.

Annex III on waste management is included in the priority area "Environment and resource efficiency":

LIFE Regulation Annex III

(B) Thematic priorities for waste: activities to implement the specific objectives for waste set out in the Roadmap to a Resource Efficient Europe and the 7th Environmental Action Programme, in particular:

(io) integrated approaches for the implementation of waste plans and programmes;

(Ii)	*activities for the implementation and the development of Union waste legislation, with a particular focus on the first steps of the Union waste hierarchy (prevention, re-use and recycling);*
(Iii)	*activities for resource efficiency and life cycle impact of products, consumption patterns and dematerialisation of the economy.*

"With regard to waste, the Roadmap to a Resource Efficient Europe and the 7th Environmental Action Programme aim to achieve the following overall targets by 2020:

- *to reduce the waste generated,*
- *maximise recycling and reuse,*
- *limit incineration to non-recyclable materials,*
- *limit landfilling to non-recyclable and non-recoverable waste.*

Priority will therefore be given to the following project topics:
Application of waste legislation - Annex III, Section A, points (b) (i) - (ii)

1. *Implementation of waste management methods (separate collection, sorting and recycling) of waste in the outermost regions of the EU or on islands with a resident population of less than 250 000 inhabitants.*
2. *Implementation of innovative solutions for one of the following objectives:*
   - *separate waste collection and recycling of electrical and electronic equipment (WEEE) and/or batteries and accumulators or recycling of WEEE and/or batteries and accumulators;*
   - *dismantling and recycling of end-of-life vehicles (ELV);*
   - *selective deconstruction of construction works or of buildings with subsequent recovery of materials or products with recycled added value;*
   - *sorting and value-added recycling of plastics;*
   - *sorting and recycling of organic waste;*
   - *recycling of composite materials to recover critical raw materials.*

Explanatory note:
In addition to these innovative solutions and to the LIFE project, other relevant waste management operations in line with the waste hierarchy should also be pursued during and beyond the project period.

3. Identification and separation of hazardous substances contained in waste, to enable the value-added recycling of treated waste and the safe disposal of dangerous substances in the framework of the project.

Waste and resource efficiency - Annex III, Section A, point (b), point (iii)

1. Implementation of new business and/or consumption models and/or approaches in support of resource efficiency, in priority industrial sectors as outlined in the Roadmap to a Resource Efficient Europe and the EU Action Plan for the Circular Economy, focusing on product durability, the reuse, repair and recycling and on alternative processes to the sale of products. Already during the project lifetime, the implementation of new business models and approaches should:
   - *lead to a reduction in the use of resources (e.g. use of materials, energy and/or water use, depending on the main effects),*
   - *support transformation in small and medium-sized enterprises (SMEs),*
   - *integrating the social dimension into the business model.*

Explanatory note:

Alternative processes include, but are not limited to, sharing or leasing, regeneration, industrial symbiosis, optimisation of food chains, transport and mobility, sustainable buildings and construction/demolition." [39]

The LIFE programme has, over the years, made a contribution to the achievement of the European targets on carbon reduction and efficiency, in terms of resources, taking an important role in the Europe 2020 Strategy and in the transition towards a circular economy.

Generating less construction and demolition waste and facilitating the reuse and recycling of materials, products and building elements, represents a key point in the circular design approach proposed by the EU [40]. Facilitating the circular use of building elements and components, not only through a reduced production of waste, but especially through high quality reuse or recycling, enables the retention of most of the value of the materials used at the end of the building's life cycle. The design of the components and the construction methods (construction phase) must therefore be aimed at achieving these objectives in order to avoid low-quality recovery.

The need to promote high quality recycling (up cycling) rather than a process of converting materials into new materials of lower quality and reduced functionality (down cycling) is also highlighted in Directive 2018/851/EU, amending Directive 2008/98/CE, which requires Member States to take measures to promote the selective demolition for waste in order to enable the safe removal and the safe treatment of any dangerous substances and to facilitate high quality reuse and recycling through the selective removal of materials, as well as to ensure the establishment of sorting systems for at least some construction and demolition waste.

"In the upcycling process, an output becomes an input into a higher value sector, and one with greater economic, functional and aesthetic value" (CIRCULAR ECONOMY REPORT - January 2021).

Of the thirty-two projects related to the theme "Construction and demolition waste" that were awarded in the period from 1994 to 2018, the largest number came from Italy and Belgium (each of the two countries received five funded projects).

Considering the European objectives related to the management of this type of waste, which aims to improve its identification, separation at source and collection, reduction, logistics and treatment as well as quality management, the projects analysed can be assessed against the following criteria:

1) prevention, in terms of upstream reduction of the waste produced;
2) testing and reduction of all toxic substances in building materials;
3) high recycling rate in terms of quantity, but low quality (down cycling);
4) high recycling rate in terms of quality (up cycling);
5) containment of energy consumption and reduction of emissions related to construction waste management. [41]

3.2.2. Winning projects of the Life programme

The 32 projects related to the topic "Waste-Construction and demolition waste", winners of the LIFE programme, were analysed below.

- 1994

The first project to benefit from the LIFE programme in the area of C&D waste was won in 1194 by Belgium - Centre Scientifique et Technique de la Construction (CSTC-WTCB). The project, demonstrating the use of recycled materials in the construction sector, for which Project Manager E. Rousseau was responsible, involved the construction of a house made entirely from recycled materials. [42]

- 1996

In 1996, Gebr. Knauf Westdeutsche Gipswerke - Germany was awarded LIFE funding with the project Recycling plant for plaster board waste from building sites and production by Project Manager Henke. The focus on plasterboard was to protect natural resources through recycling and to deliver less waste to disposal sites by pulverising it and feeding it back into the production process.

- 1997

The project OEKO - Waste management in the field of construction with prevention as a main goal, proposed by Luxembourg in 1997 and carried out by Project Manager: Marc Simon aimed to demonstrate how, through careful planning of the actors in the construction process, it is possible to develop methods of separate collection for the recovery of construction site waste. The results show that: "*The project was developed on four sites at the same time comprising a total of 231 private flats and a shopping centre. The General Contractor was the "Fonds du Logement" (Housing Fund) of Luxembourg. A total of 254 guidelines were established to translate the theoretical objectives of waste prevention into concrete actions. The results show that the architects and engineers adopted 216 of these to apply on the construction site: at the end 114 of the directives were fully implemented, 57 were partially implemented and 45 were not implemented at all.*" [OEKO - Waste management in the field of construction with prevention as a main goal. LIFE97 ENV/L/000206]. The final review also reveals the problems, encountered during the implementation, mainly related to traditional approaches and common uses that are difficult to unravel for both technicians and operators. Interest and attention to the issue of C&D waste, however, has not been abandoned over the years. On the sdk.lu website, in fact, in addition to several sections all dealing with environmental issues, there is a section dedicated to waste management on construction sites with the "SuperDrecksKëscht® fir Betriber Concept" created following the implementation of a Luxembourg law on waste management of 21 March 2012 which states that the prevention, reuse and recycling of construction and demolition waste should be promoted in accordance with the following hierarchy:

Figure n. 6 - Implementation hierarchy. Source sdk.lu

What the concept offers, essentially, is on-site consultancy including the inspection phase, volume assessment, collection design and training, monitoring and management, for both construction and demolition sites.

- 1998

Ireland's only contribution to the LIFE programme was in 1998 with the project "Demcon 20/20 - Recovering and recycling construction and demolition waste" under the supervision of project manager Liam Dromey of Cork City Council, the municipal authority responsible for County Cork. The project arose from a twofold need, on the one hand to solve the local C&D waste problem after having estimated the production of around 500,000 tonnes of C&D waste in 1998, and on the other hand to develop a new use for the landfill site, which existed at that time but was in the process of being decommissioned. These needs were to be resolved through the construction of a new C&D waste treatment plant, the development of a pilot programme for the re-use of this surplus and the construction of a new attraction on the site of the old landfill. The results found in the EU database show that, completed in 2002, the plant was successfully built and operated throughout the entire duration of the project and that some of the surplus already present in the old landfill was reused for the construction of small facilities on site. In spite of these positive aspects, the project encountered several obstacles that compromised the achievement of its objectives, including the difficulty in creating a market for recycled materials due to the presence of cheap raw materials and a "*historical distrust of recycled material*". Currently, the dedicated website is no longer active.

In 1998, a contribution also came from France with the project "GIRAUD SA - Good on-site waste management practices" by Giraud S.A., a French company specialised in foundations [38-42]. The objective is to develop concrete methods for the re-use of construction site surpluses in order to establish a methodological model of good practice through training activities. The project is divided into 3 activities: training activities and application of the method with the development of a manual, worksite experience activities with the dissemination of information documents, at the end of which a document was produced on the 15 construction sites used to test different methods for waste management, analysing the disparities between the expected waste and the quantities actually produced. The final report clarified delays in the opening of the project's work caused by the difficulty of selecting the sites and at the same time the need to train the operators. The third activity concerned the drafting of a purely practical and operational methodological manual, "Good practices for waste management at construction sites", divided into 4 modules: distinguishing different types of waste; waste management; waste management follow-up; verification of good waste management. The results showed that the measures put in place lead to a reduction in the cost of waste disposal by 50%, which translates into a modest saving of 0.5% on the overall cost of construction sites; at the same time the amount of waste produced on construction sites can be reduced to one third; recycling of materials can only be carried out on the premises of large construction sites; special waste (e.g. wood, window grills, cables, central iron, inert materials) can be sorted in large quantities. In terms of environmental benefits, based on the experiences of the construction sites, the results were "resoundingly positive". The new measures implemented according to the project guidelines reduce the cost of waste disposal by 50%, a modest saving of 0. 5% of the total costs for the construction sites. Source: Focus: "A cleaner and greener Europe" (2004).

In the region of Catalonia, Spain, more than three million tonnes of construction and demolition waste were recorded in 1998. Despite the promulgation of an adequate regulatory framework due to a lack of resources and difficulties within the sector, the rules are not properly enforced, leading to disastrous conditions in which inert construction waste is mixed with other contaminating and toxic waste and deposited in inadequate containers or dumped in illegal sites. The Instituto de Tecnología de la Construcción de Cataluña has therefore undertaken to raise awareness among the construction industry through the publication of several contributions, including the "Recommendations for the reduction and effective management of residues from new build and demolition", a manual for the management of C&D waste.

- 1999

In 1999 Netherlands won the Life programme with the Reflex houses project. [48]. In 2002 the thirty-eight Reflex-houses were sold, with the exception of the exhibition house which was opened to the public. The Reflex-house concept underlying the project provides four types of flexibility:

1. spatial flexibility: change of layout thanks to removable partitions; variability of volume by adding an industrially produced "on top" and/or "add-on" module;
2. technical flexibility: the choice of built-in components remains flexible throughout the life of the house;
3. functional flexibility;
4. emotional flexibility: offering the possibility to organise the home according to wishes and needs, and to change it easily in the future.

The quantified environmental benefits were significant: using the Eco-Quantum method, a computer programme that calculates the environmental impact of a residential building and translates these effects into environmental standards and effects, taking into account the amount of waste generated during the lifetime of the houses, it was shown that the EQ-score of the houses is two EQ-indicator points lower than that of traditional houses. However, it is believed that the real environmental benefits are higher as the Eco-Quantum method does not fully take into account the environmental benefits of increasing the lifetime and flexibility of the houses. Concerning the amount of waste produced during the construction phase, the total amount of waste for each house in this project was 8.9 m^3. This is not a considerable reduction compared to traditional construction projects and this figure does not meet expectations as stated at the beginning of the project, but an explanation can be found in the innovative and experimental character of the project.

Very interesting are the data coming from Finland. From October 1999 to September 2002 it established a recycling site with a shredder and supporting equipment for waste treatment. The automation of the separation of waste fractions in spite of the appropriate equipment still required a lot of manual work. The main result of the project, however, was the creation of a continuous waste chain from the construction and demolition sites to the end users of the sorted and treated waste fractions. The project received about 10,000 tonnes of waste per year, of which about 83% was treated for further use and the remaining 17% was landfilled; most of the treated waste went to feed small power plants. A subsequent ex-post evaluation, carried out in June 2004 by LIFE's external monitoring team, showed the results to be as follows:

a. the volumes of waste received and treated remained at around 10,000 tonnes per year;
b. the recovery rate increased slightly, approaching 90% of the waste received. This result was achieved thanks to more careful sorting, mainly by hand, which also involved additional work and resulted in a higher number of fractions than what was originally planned;
c. some mechanical improvements were also made to the process: a specific mechanical sieve, through which some waste fractions are passed, separates mineral substances (tiles, plaster, bricks) or their remains from the waste material so that the usually clean and homogeneous mineral waste fraction can be easily sold for infrastructure construction.

Also in 1999, Belgium, in order to overcome a problem concerning C&D waste in the construction of roads, undertook to promulgate guidelines proposing tools and methodologies. The establishment of pilot sites allowed an assessment of the costs and materials required and, although the project did not bring about a real change in practice, it did achieve its objective of raising awareness and spreading know-how.

In addition to those analysed above, there have been many others over the years, which can be viewed in the EU archive.

3.2.3. Italian contribution to the Life programme

- 1998

The first winning project of the LIFE programme in Italy is WAMP - VAMP: Valorisation of building demolition materials and products [49]. The objective to be achieved was to develop, within a limited geographical area of the Emilia Romagna region, a management system for recoverable waste in the C&D (construction and demolition) sector, in order to reduce the amount of undifferentiated waste and valorise it for possible reuse. At present no documentation has been found that would be useful to understand and analyse the project phases and the results obtained.

- 2010

As part of the LIFE+ project, Italy's response, through the company Saint Gobain PPC Italia S.p.A., is to build three plants to recover waste from demolition, as part of the Gy.Eco project, which came into being following the entry into force of Legislative Decree 152/2006 and Legislative Decree 36/2003. The objectives include: "*The Gy.Eco project aims to develop a system for the management and treatment of plasterboard and plaster residues from construction activities. This process could allow the recovery of gypsum for reuse as an additive in cement production."* [50] *"The Gy.Eco project plans to develop a recovery process and a management system capable of treating 15,000 tonnes/year of residual plasterboard in three pilot plants and recovering about 14,500 tonnes/year of plaster for re-use"* thus recovering about 95% of the waste material. In fact, the service intended to be offered includes both the creation of a logistics network for the transport service to the three sites they manage, including the area of the Molise Region, the provinces of Pesaro and Urbino and the Piedmont Region, and also the creation of an itinerant recovery plant.

As mentioned above, the main problems stem from bureaucratic slowness, which was also found in the case of Gy.Eco in the 2016 final report states: *"The main problems encountered in this action were the delays in the authorisation process. All the authorities involved in authorising the recovery activities have shown their difficulties in closing the authorisation files within the timeframe required by the legislation, which therefore lasted well beyond the five months required by Legislative Decree 152/2006. As regards the Sassofeltrio site, in addition to the slowness of the Authorities responsible for the analysis of the files, the delays are also due to changes in the regional regulatory framework for the issuance of the Authorisation itself, extending it for more than 12 months. As far as the Montiglio site is concerned, the greatest delays are attributable to the change of competences from the Region to the SUAP (Unique Service for Productive Activities), which led to a de facto cancellation of the procedure, which then began all over again with the transfer of competences from the Region to the SUAP mentioned above, with an inevitable extension of time. The authorisation for the Guglionesi site was obtained on time, thanks to the early start of the same procedure. However, this administration has also undergone a series of internal changes which have slowed down the time taken to issue authorisations since, as in the case of Montiglio, each time the files were resumed and the procedure therefore started practically from the beginning. As a result of these delays, obviously, and as already mentioned in the Midterm Report,* *there was also a slowdown in the time taken to make investments and therefore to incur expenses, particularly as regards the purchase of infrastructure and equipment and the depreciation accounting procedure. In addition, the staff of the sites started working later than planned, causing, also in this case, a delay in the related expenses. The delays in the authorisations, which have caused the postponement of the opening of the recovery sites and therefore of the very operation of the Gy.Eco service on the national territory, as well as the delays in the expenses to be incurred for the implementation of the sites, have made it necessary to request a one-year extension for the closure of the project."* [51]. It has been deemed necessary to mention this fragment of the report as a testimony to the real problems that all too often cause loss of funds and/or increased expenses.

The details of Gy.Eco are not reported here, but the whole project, including the analyses carried out, is of considerable interest and should be studied in depth.

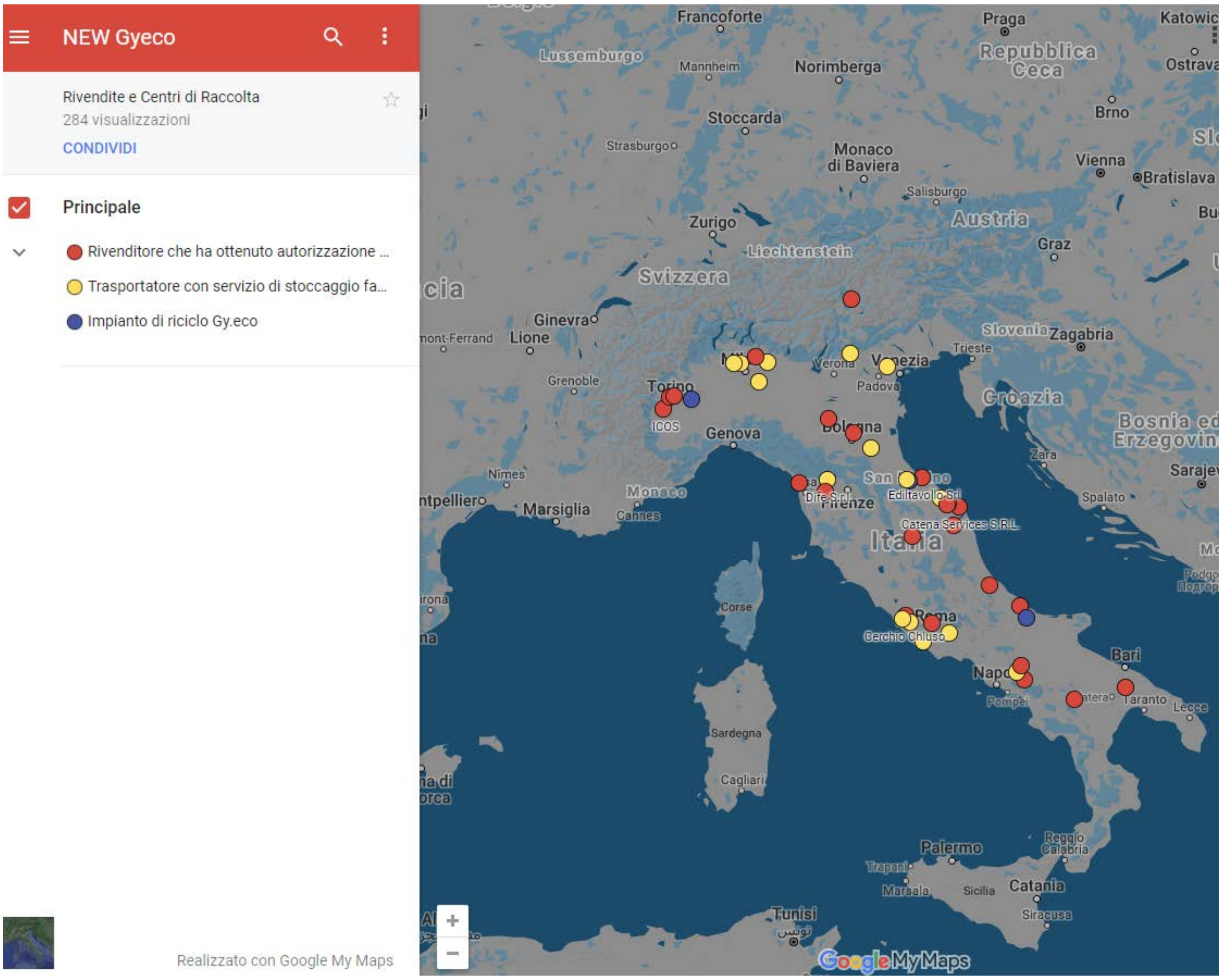


Figure n.7 - Current Gy.Eco retailers and collection points. Source ww.gyeco.com

- 2013

In 2013 Mamma Rosa's Project S.r.l. in collaboration with CERAMICA FONDOVALLE S.p.A., the University of Modena and Reggio Emilia and the University of Padova, raised the issue of reusing heterogeneous glass, i.e. with high levels of contamination. The answer to this problem was LIFE in SustainaBuilding - Sustainable Recycling in the Polyvalent Use of Energy Saving Building Elements. The objective was to produce innovative high-performance building materials, in this case demonstration products (tiles, bricks) containing 95% glass waste. During the project phase, several materials were identified, such as: silicon powders from metallurgical powders, glassy materials, glassy ceramics or contaminated ceramics, lime from filters and other foaming agents; starting from these materials, after a series of experiments, a mixture was obtained which allowed the realisation of samples derived from recycled materials. Below are the results of the project which ended on 31 January 2017:

"The project has led to important results. In fact, it has made it possible to demonstrate a technique that makes it possible to produce construction elements of two different types (the first is more expanded and the second is pressed and more compact) using waste glass and other recycled products. In particular, the new products:

- *are made up of approximately 90% miscellaneous waste and scrap;*
- *are obtained from a production cycle involving low reactive sintering temperatures so as to minimise Embodied Energy estimated at values close to 5 MJ/kg;*
- *have an apparent density between 0.4 and 1.2 g/cm3;*
- *they have a thermal conductivity varying between 0.1 6 and 0.21 W/mK, with excellent insulation performance, especially with reference to the expanded product type;*
- *they have a compressive strength of up to 2,7 MPa and can therefore be used in structural applications with light loads or for self-supporting structures;*
- *are insulating elements that do not contain fibres and do not disperse dust, making them more biocompatible for human health than fibre-based products;*
- *they are completely recyclable at the end of their life through a simple grinding treatment, reintroducing them within the same production cycle;*
- *they lead to a significant reduction in solid waste because any waste generated during production can be reused;*
- *they also lead to a significant reduction in energy consumption (up to 30%) due to the significant lowering of the sintering temperature;*

- *they can be coloured both in mass, with regard to expanded products, and superficially, with regard to pressed products.”* [52]

In the same year, the Life Is.eco - Isover for recycling and ecosustainability project examined the reuse of bituminous materials and glass fibres, with the aim of creating recycling centres in the Saint-Gobain Isover Italia plants in Vidalengo and Chieti. The Layman report shows the value of the project: the treated materials, which are considered special waste, have as their only final destination the disposal in a controlled landfill. Instead, the in-plant process aims to valorise these "rejects" through specific treatment operations, to repurpose them and transform them into new raw materials. The results have seen approximately 1,500 tonnes in two years of mineral wool waste transformed into flock and reintroduced into the production cycle and more than 130,000 mq/year of membrane-based waste also brought back into the production cycle, leading, among other things, also to a considerable reduction in the areas occupied by landfills. The project and its results have been very successful. A post-LIFE communication plan was produced on 31 May 2018 with the aim of promoting the project and carrying on this collection, transport and treatment system, addressed on the one hand to the professionals and businesses that represent the active party, and on the other to the administrations so that they are kept up to date on the progress and results obtained. What emerges from the technical report is the problem linked to the bureaucratic component, as we read in fact: *“The main obstacles to be tackled are represented first of all by the administrative hurdles due to the authorization request needed to recover waste produced by third parties or, in any case, to the implementation or modification of an integrated environmental authorization, which often take longer than required by law. Another obstacle to be tackled is surely represented by the continuous changes in national regulations on landfills which, although linked to an adjustment of European Directives, are then postponed from year to year, thus de facto always allowing waste disposal in landfills and not promoting alternative solutions aimed at recovery. It should also be kept in mind that anyone wishing to implement a system for recovering bituminous membrane or glass wool wastes without having production plants must cooperate with the companies that manufacture the respective building products. This can be not only a technical obstacle but also a bureaucratic one, because in order to sell a recovered product as a "product" there must be a specific End of Waste decree, which is currently lacking in Italy.”* [53]; these considerations, published at the end of August 2018, paint a very demoralising portrait of bureaucracy and of the range of tools on offer.

- 2014

Another project born in Italy and funded in 2015 is LIFE ECO TILES - innovative ECO methodologies for the valorisation of construction materials and urban waste into high-level TILES, in collaboration between the University of Camerino and the company Grandinetti, which deals with the production of traditional and artistic tiles. The aim of the project is to produce prefabricated tiles with 77% recycled materials, cement, glass, ceramics and construction and demolition waste (CDW), ensuring a 20% lower environmental impact than traditional techniques. In September 2016, the project saw the presentation at the Cersaie fair, of its first two products "fiasco" (20 × 20 cm, recycled green glass) and the second " lunotto" (40 × 40 cm, colourless car glass). Throughout 2016 and 2017, the project was promoted in various locations, arousing great interest, a sign of an increasingly strong desire to approach new technologies. The results obtained showed a product that can replace cement-based materials so well that it was selected for the flooring of the "Museum of Production and Electricity" in S. Severino Marche (Italy). [54]

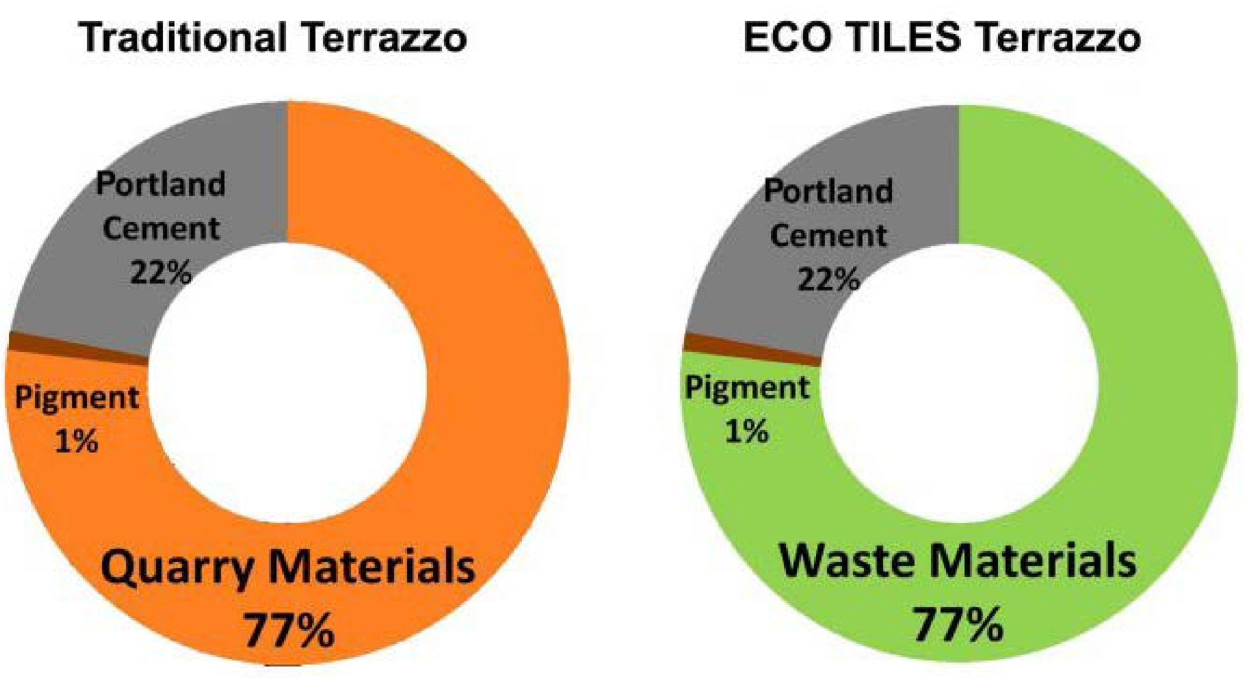


Figure n.8 - Comparison between the traditional system and the EcoTiles system. Source www.ecotiles-lifeproject.eu

The five Italian projects covering the topic of “Waste Construction and demolition waste ", winners of the LIFE programme, were found to be extremely interesting, even though they did not respond in the same way to the evaluation criteria identified in the previous paragraph. Table 1 shows the ability of each project to meet the different requirements. [41]

		Criteria				
		Prevention	Reduction of toxic substances	Down cycling (quantity)	Up cycling (quality)	Reducing consumption and emissions
Project	1998 WAMP - VAMP	●				
	2010 Gy.Eco			●		
	2013 SustainaBuilding	●			●	●
	2013 Life Is.eco	●			●	
	2015 Life Eco Tiles				●	●

Table n.1 - Compliance of the Italian projects analysed with the identified criteria

3.2.4. Italy in the management of building industry surpluses

In Italy there are several other examples of applications that originated outside the European LIFE programme. In March 2007, the Environmental Commission of the Construction Group of Assindustria Udine drew up guidelines with the aim of providing a small guide as a support tool for operators [55] which, for example, recommends adopting selective demolition in order to recover aggregates more easily and reuse them after treatment as construction materials instead of natural aggregates. In particular, the guidelines report some examples of recovery such as the case of milled material for which *"the recovery activity can currently be undertaken after 90 days from the communication made to the Register of Environmental Managers (Article 216 - Environmental Code). The operator of the plant must take care to separate the waste from the MPS obtained from recovery and to properly manage the administrative documentation proving the proper management of the plant itself (transport forms, registers, MUD, analysis ...). The storage of waste at the plant inlet must follow the precise technical rules of Annex 5 of Ministerial Decree 5/2/98 and subsequent amendments and additions. The storage of MPS leaving the plant follows the normal rules of material storage. The release test for the re-use of the milled material is given by the following parameters (letters b and c of point 7.6 cited above).*

PARAMETERS	***UNITS OF MEASUREMENT***	***LIMIT CONCENTRAZIONS***
Nitrates	*Mg/l NO3*	*50*
Fluorides	*Mg/l F*	*1,5*
Sulphates	*Mg/l SO4*	*250*
Chlorides	*Mg/l Cl*	*100*
Cyanides	*micrograms/l Cn*	*50*
Barium	*Mg/l Ba*	*1*
Copper	*Mg/l Cu*	*0.05*
Zinc	*Mg/l Zn*	*3*
Beryllium	*g/l Be*	*10*
Cobalt	*g/l Co*	*250*
Nickel	*g/l Ni*	*10*
Vanadium	*g/l V*	*250*
Arsenic	*g/l As*	*50*
Cadmium	*g/l Cd*	*5*
Chromium	*g/l Cr*	*50*
Lead	*g/l Pb*	*50*
Selenium	*g/l Se*	*10*

Mercury	*g/l Hg*	*1*
Asbestos	*Mg/l*	*30*
COD	*Mg/l*	*30*
PH		*5,5 - 12*

The example of washing silt is cited as a result of the washing of gravel, and it is underlined that it is possible to use the silt, which is considered waste, as a material that can be used in construction within the parameters of the regulations.

In February 2009, the Waste Management Plan (later updated in 2011 and 2013) was developed for the Final Project of the new embankment of the right bank of the Po River, downstream of the motorway junction in the municipality of Moncalieri, by the associated firm DIZETA INGEGNERIA. In this particular case, the first step was to preliminarily analyse the individual work phases and the relative waste materials, for each of which a table was drawn up containing the type of waste, the relative CER code, the description according to the CER catalogue, the classification of the waste, the final destination and the type of recovery or disposal. The report shows that, in the case of deforestation and brush-clearing activities, the material produced, which is biodegradable of nature, can be recycled and used for the production of compost, while the bituminous materials can be used for the production of new bituminous conglomerates or as aggregates for road foundations, while for all the ferrous scrap, a possible recovery or sale to the scrap market is envisaged.

In 2012, the Green Building Council Italia Association developed a guide for the drafting of a construction waste management plan in which strategies to minimise waste production are identified. [56]:

- perform multiple functions with one material rather than requiring multiple materials to perform one function and optimise the use of systems and components;
- if possible, use standard-sized materials and products to reduce special cuts and assemblies, which create waste;
- select systems that do not require temporary supports, shoring, building supports, or other materials that will be disposed of as waste during the project;

- use assembled prefabs, manufactured off-site (when possible) to avoid waste generation on site;
- choose materials that do not require adhesives, require containers and create residues and packaging waste;
- choose materials with integrated finishes to reduce the need for applied finishes, laminates, coatings, adhesives, and associated waste, packaging and scrap;
- avoid materials that are easily damaged, susceptible to environmental contamination or exposure, dirty, and which increase the potential for site waste.

In addition to a series of indications on how to carry out activities at the worksite and recommendations on collection sites and documentation to be produced, the following example table (Figure n.9) is attached for the treatment of each individual worksite material.

In 2014, the Province of Piacenza developed a series of Technical-Organisational Provisions in which substantially the definitions and tasks of the various figures involved are reported; the correct compilation of the Waste Identification Form (FIR) is illustrated. With regard to the re-use of rubble, it specifies that: *“Tall subjects producing material deriving from construction and demolition works, including road constructions, must adopt all measures aimed at favouring the reduction of waste to be disposed of in landfills, through reuse operations, subject to verification of the technical compatibility of reuse in relation to the type of works envisaged... The use as such of rubble deriving from construction and demolition is strictly forbidden. Demolition waste, in order to be reused, must be treated in special crushing and sorting plants. The possibility of obtaining secondary raw materials (MPS) from this waste is provided for by a specific technical standard, Ministerial Decree 05/02/1998, through mechanical and technologically interconnected phases of grinding, screening, granulometric selection and separation of the metallic fraction and the undesired fractions to obtain inert fractions of a stone nature with a suitable and selected granulometry". In addition, with regard to the procedures, he adds: "... it is allowed to reuse, at the same production site, inert materials from demolition and construction for the construction of yards, foundations, embankments, tracks, roadbeds, levelling, terracing for construction purposes, ground granules and so on - without this constituting a waste recovery activity”*. This is only possible if there is a certainty of re-use before the works are carried out; guaranteeing the minimum suitability requirements of the materials through the declaration of re-use on site of inert materials generated by demolition and construction activities.

The most virtuous example comes from the Autonomous Province of Trento which, unlike other regions, has up-to-date waste management plans and has worked to develop ad hoc specifications; in this regard, for the use and production of recycled aggregates, the Autonomous Province of Trento has drawn up and approved specific Technical Environmental Regulations. This action, together with the strong presence of recovery plants in the area, has led to a percentage of waste destined for recovery of over 70%.

Tabella per la gestione dei rifiuti in cantiere

Materiale	Quantità	Metodo di smaltimento / Nome destinatario	Procedura di gestione / Codice CER
Terreno di scavo		Tenere separato per il riutilizzo e / o la vendita	Tenere separati in aree designate sul sito
Legno		Tenere separato perché venga riutilizzato	Tenere separati in aree designate in loco. Posizionare nel container riportante il codice CER di riferimento, il nome del contenuto (legno) ed un'immagine esemplificativa.
Compensato, OSB, pannelli di truciolare		Riutilizzo, discarica	Parte di riutilizzo: Tenere separato nelle aree designate in loco. Parte di discarica: Mettere nel container riportante il codice CER di riferimento, il nome del contenuto ed un'immagine esemplificativa.
Legno verniciato e/o trattato		Riutilizzo, discarica	Parte di riutilizzo: Tenere separato nelle aree designate in loco. Parte di discarica: Mettere nel container riportante il codice CER di riferimento, il nome del contenuto ed un'immagine esemplificativa.
Calcestruzzo		Riciclare al: Centro riciclaggio "Calcestruzzi"	Tenere separato nelle aree designate in loco. Mettere nel container riportante il codice CER di riferimento, il nome del contenuto ed un'immagine esemplificativa.
Metalli		Riciclare al: Centro riciclaggio "Metalli"	Tenere separato in aree designate in loco. Mettere nel container riportante il codice CER di riferimento, il nome del contenuto ed un'immagine esemplificativa.
Vernici ed isolanti		Riutilizzare o riciclare al Centro riciclaggio "Vernici ed isolanti"	Tenere separati in aree designate in loco. Mettere nel container riportante il codice CER di riferimento, il nome del contenuto ed un'immagine esemplificativa.
Pavimentazioni		Riutilizzo, discarica. Riciclare al: Centro riciclaggio "Pavimenti"	Tenere separati in aree designate in loco. Mettere nel container riportante il codice CER di riferimento, il nome del contenuto ed un'immagine esemplificativa.
Tappeti e moquettes		Riutilizzare o riciclare al Centro riciclaggio "Tappeti & Moquettes"	Tenere separati in aree designate in loco. Mettere nel container riportante il codice CER di riferimento, il nome del contenuto ed un'immagine esemplificativa.
Vetro		Riciclare al: Centro riciclaggio "Vetro"	Tenere separati in aree designate in loco. Mettere nel container riportante il codice CER di riferimento, il nome del contenuto ed un'immagine esemplificativa.
Plastica		Riciclare al: Centro riciclaggio "Plastica"	Tenere separati in aree designate in loco. Mettere nel container riportante il codice CER di riferimento, il nome del contenuto ed un'immagine esemplificativa.
Contenitori di bevande		Riciclare al: Centro riciclaggio "Contenitori bevande"	Tenere separati in aree designate in loco. Mettere nel container riportante il codice CER di riferimento, il nome del contenuto ed un'immagine esemplificativa.
Cartone		Riciclare al: Centro riciclaggio "Carta&Cartone"	Tenere separati in aree designate in loco. Mettere nel container riportante il codice CER di riferimento, il nome del contenuto ed un'immagine esemplificativa.
Carta e carta di giornale		Riciclare al: Centro riciclaggio "Carta&Cartone"	Tenere separati in aree designate in loco. Mettere nel container riportante il codice CER di riferimento, il nome del contenuto ed un'immagine esemplificativa.
TOTALE			

Figure n.9 - Table for construction site waste management, Green Building Council Italy Association

3.3. Geopolymers: first applications

In the last few years, there has been a great development of a new type of binders called 'geopolymers' [57]. Geopolymers are alumina-silicate-based materials characterised by a three-dimensional cross-linked structure. The suffix "geo" implies that geopolymers simulate natural rocks in their chemical composition and mineralogical structure, from which they exhibit the main properties such as hardness, chemical stability and durability. The term polymer, on the other hand, indicates the type of consolidation process, known as 'geopolymerisation', which shares kinetics and mechanisms with polymerisation by polycondensation. Some theories, which have not yet been confirmed, trace the use of geopolymers back to very ancient times. In 1978, Joseph Davidovits of the Geopolymer Institute in Saint-Quentin (France), on the basis of some of his studies, invented the term 'geopolymers' to refer to inorganic polymers produced artificially from aluminium-silicate compounds. But as far back as the 1950s, Victor Glukhovsky, a Ukrainian researcher at KICE (Kiev Institute of Civil Engineering, in the former URSS), studying the differences between ancient binders and modern concretes, came up with the synthesis of various aluminosilicate binders from clays, feldspars, volcanic ash and various types of slag, to which he gave the name "soil silicate concretes" and "soil cements" [58]. But what initially made Davidovits famous, a chemist with a passion for archaeology, was his theory on the use of geopolymeric mortars in situ in the construction of the famous and majestic pyramids of the Giza Plain in Egypt, believing the use of large stone blocks to be highly improbable, as is the most widely accepted theory to date [59].

Recent studies [60] have shown that geopolymer binders can be obtained from natural raw materials (e.g. pozzolan) and synthetic raw materials (metakaolin), as well as from secondary raw materials such as industrial waste (coal combustion fly ash and blast furnace slag) and excavated materials. Other applications of geopolymer binders include their use as fire-resistant materials, thermal insulation materials, composites for the renovation and reinforcement of buildings and artefacts of historical interest [61-62].

In analogy to zeolite materials, geopolymers can also be used for the stabilisation/energisation of toxic waste and the immobilisation and storage of hazardous waste by acting as an alkaline stabiliser to convert semi-solid and/or powdery waste into a cohesive solid [63].

Excellent results have also been obtained in the stabilisation of dredging sludge, quarry and mining waste [64] [65] [66] [67]. These new types of eco-sustainable alkaline-activated binders could, in the coming years, contribute to bridging the current gap between Aurora and other countries such as Australia (a country at the forefront of the use of geopolymeric binder materials) and the United States, which have already been using geopolymers for several years, for example in the construction and repair of motorway surfaces and airstrips, among others; one of the most successful products for this type of application has been Permeant® geopolymer cement, developed between 1980 and 1990 by Lone Star Industries Ltd. , one of the leading American cement companies. One of its earliest uses was in the construction by US Air Force Engineering of a temporary military airfield during the Gulf War [68-69]. More recently, the Australian Rebound Group released E-Crete, geopolymer cement, based on fly ash and not containing Portland cement, for more general uses, such as paving pavements or paths, prefabricated elements and sound barriers [68].

3.4. The use of geopolymers in the construction world

Geopolymers represent an important alternative to reduce emissions and energy consumption, while respecting the properties of the mixtures [70], at the same time ensuring the achievement of high mechanical performance. The production of geopolymers allows an 80% reduction in emissions compared to the production of Portland cement [71]. What characterises and distinguishes this innovative cement from Portland cement is, in particular, treatment at much lower temperatures (max. 60 - 80°C) and CO_2 emissions that are 80% or more lower [72].
Similarly to what has been seen for materials with pozzolanic activity (MAP), materials deriving from the recycling of ceramic industry waste or the "ceramic" fraction of demolition waste could also be used in the production of mortars or geopolymer conglomerates, as demonstrated by several research projects conducted in recent years; for example: Mater SOS - Sustainable materials for the restoration and construction of new buildings, a project funded by the Emilia-Romagna Region's POR-FESR 2014-2020 and coordinated by the Bologna Ceramic Centre, whose aim was to reduce the environmental impact of materials and components used in construction, operating a product innovation based on the use of waste materials treated as secondary raw materials in accordance with the principles of the circular economy [68]; InnoWEE - Innovative pre-fabricated components including different waste construction materials reducing building energy and minimising environmental impacts, a project financed by the EU under the "Horizon 2020" Research and Innovation Programme and coordinated by ISAC - Institute of Atmospheric Sciences and Climate of the Italian National Research Council (CNR), which aimed to recycle waste from the construction and demolition of buildings, based on new formulations in geopolymer technology, in terms of economic feasibility, performance and technological advancement; RE4- REuse and REcycling of CDW materials and structures in energy efficient pREfabricated elements for building REfurbishment and construction, also funded by the European

Commission under the "Horizon 2020" Programme and coordinated by CETMA - European Research Centre for Technology, Design and Materials in Brindisi, focused on the development of new technologies for prefabricated elements with a high component of materials from demolition waste in order to develop energy efficient buildings able to mitigate the environmental impact of the construction industry [59].
Chemically bonded ceramics (CBCs), then, belonging to the class of AAMs, are a group of inorganic materials that share properties with both cements and ceramics [73]. The formation of CBCs occurs chemically, just as with conventional cements, while the chemical bonds and mechanical properties resemble those of ceramics. These materials allow an alternative route for processing ceramics, where high temperatures are not required, and solid structures formed at room temperature in the presence of mineral impurities.
Moreover, studies have been found showing that geopolymerisation is a viable way to add value to waste, giving rise to materials with high mechanical strength, high chemical inertness and allowing the encapsulation of other wastes, including hazardous ones [74], [75], and also, studies on the manufacture of geopolymers with waste generated by the ceramic industry [76], [77], [78], [79], [80].

3.5. Patents

Using the keywords “Demolition waste geopolymer”, the databases considered for the analysis and in-depth study of the state of the art were:

- https://patentscope.wipo.int/search/en/search.jsf
- https://worldwide.espacenet.com/

Patent scope

A search using the keywords "demolition waste geopolymer" produced no results, so it was decided to change the word "demolition" to "construction". This search produced fifty-one results, covering the period from 2012 to 2021. Of these, nine are the most relevant to the research and will be briefly presented below in order of decreasing relevance to the topic.

Patent “Construction waste red brick powder and coal ash geopolymer material and preparation method thereof” is produced from red brick powder with a proportion of 65% and fly ash, marine sand, concrete and artificial sand as aggregates, solid water glass powder as an alkali activator, and metakaolin as an additive. The raw materials by weight: 1-70% of the red brick powder, 1-80% of the coal ash, 1-96% of the marine sand or artificial sand, 1-20% of the solid water glass powder, 5-50% of water and 5-20% of the metakaolin, and the total weight percent of the red brick powder, the coal ash, the marine sand and artificial sand is 100%. With respect to the parameters of compression and bending, it was assessed that as the fly ash increases, these values increase, which is to be expected. The aggregate that returned the highest values of mechanical performance was concrete. The geopolymer material with fly ash and red bricks prepared according to the best mixing ratio was used as a masonry mortar and its adhesion to the limestone sand bricks reached 4.8MPa, far exceeding the national standard in China.[81]

Patent “Geopolymeric concrete based on recycled aggregate and preparation method of geopolymeric concrete” proposes a polymer concrete with high compressive strength, low shrinkage, excellent RAC freeze-thaw resistance, acid and alkali corrosion resistance and the cost is lower than Portland cement. The amount of waste aggregate is 40/70%. The prepared recycled aggregate geopolymer concrete has a short setting time between 10-60 minutes at room temperature; it has a high initial compressive strength, at 4 hours it is greater than 10Mpa, after one day it is greater than 15 Mpa, after 3 days it is greater than 40Mpa and after 7 days it is greater than 80Mpa. The shrinkage rate during the setting time is low, less than 0.05%; the water absorption rate is low, less than 3%; the resistance to acid corrosion, 10% sulfuric acid solution, is less than 0.01%.[82]

Of great relevance to this research is the patent 'Construction waste recycled composite admixture based geopolymer concrete'. In fact, the patent proposes a composite admixture based polymer concrete for the recycling of construction waste. In particular, the recycled composite admixture consists of raw materials such as: construction waste, fly ash, steel slag from the electric furnace, basalt. In particular, the construction waste used is cement, sintered bricks and decorative slag. [83] Also relevant to the research is the patent 'Method for preparing geopolymer cementing material from regenerated micro-powder', which proposes a geopolymer with 30-70% blast furnace slag. [84]

Although dating back to 2013, the patent 'Geopolymer concrete using recycled aggregate, capable of obtaining heavy metal elution resistance and a manufacturing method thereof' is highly topical and of considerable research interest. The invention in fact proposes not only a production method, but above all aims to use the fine powder of concrete waste as a raw material. The results show that the combination of fine powders and recycled aggregate gives satisfactory mechanical values, but lower than those achieved using powders alone. However, it was found that the amount of recycled aggregate used in the condition of maximum compressive strength is 21% by weight, which is very low recyclability, so the expected effect is low in terms of business. [85]

The “eco-efficient geopolymer bricks” patent was created with the aim of reducing flyash disposal in India. The proposed geopolymer consists of flyash, marble sludge powder, manufactured sand (as a substitute for river sand) and of course the activating solution in a ratio of 1:3. They are cured at 90° for 24 hrs, at the end of this period they are less heavy than normal bricks, with less water absorption and high compression values. [86] Similar invention, in terms of the type of industrial waste to be recovered, flyash, is the Chinese patent “Reinforced fly ash based geopolymer and preparation method thereof” [87], in which Portland cement is also used. The invention "Sound insulation mortar prepared by recycling waste incineration slag and preparation method of sound insulation mortar" describes a sound insulation mortar prepared by recycling waste incineration slag including: wood chips and fibre parts. The production of this mortar allows the use of a large quantity of incineration waste. [88] And finally the “Non-burning permeable bricks and preparation method thereof” patent that uses demolition waste as an aggregate. [89]

Espacenet Worldwide

In the evaluation of environmentally sustainable technologies, the Espacenet research also took into account the amount of energy spent during the material's production processes, so patents involving extensive pre-processing or high-temperature baking were discarded.

A search for the keyword "Demolition waste geopolymer" on Espacenet resulted in a total of sixty-three patents published between 2009 and 2021. Of these sixty-three analysed patents, eight were the closest to the topic.

The patent published in 2009, Geo-polymer recycled concrete and preparation method thereof, uses coarse and fine aggregates of recycled concrete, fly ash and slag dust as raw materials to provide silicon phase and aluminium phase, and sodium silicate and sodium hydroxide as excitation components of the fly ash. The patent also provides for the use of naphthalene sulphonate formaldehyde condensate and calcium sucrose which, added during preparation, improve workability in the mixing phase. [90] The patent, Alkali-activated cement utilising abandoned clay brick powder and preparation method thereof, of great interest for this research, uses waste clay brick powder with a mass percentage of 10% to 30% which is mixed with high calcium fly ash with a mass percentage of 70% to 90%. [91] The patent Alkali-activated fly ash-based cementing material mixed with recycled coarse aggregate and preparation method thereof [92], aims at the realisation of a cementing material based on fly ash and building waste materials. The data produced show good compressive strength to the extent that it reaches the strength grade of ordinary Portland concrete C45. Of great interest are the evaluations of the temperature conditions, in fact it is written that as the curing temperature increases, the compressive strength of geopolymer concrete can improve significantly, but if the temperature is increased too much, the compressive strength will increase slowly or even decrease. This is mainly due to the fact that high temperature curing can accelerate the chemical reaction between the first fly ash and the alkaline activator and promote densification of the microstructure.

The patent Method for preparing concrete from geopolymer and recycled aggregate provides a process for preparing concrete by combining a geopolymer and recycled aggregate. To substantially reduce the cost of concrete products and achieve reuse of construction waste. [93] Also in 2018 with the patent Recycled concrete and preparation method thereof, it is intended to provide a geopolymer concrete preparation method that has the advantages of fast setting time and high initial strength, in fact from the experimental results the 7-day compressive strength of recycled concrete exceeds 55 MPa, the initial setting time is 17-28 minutes and the final setting time is 38-53 minutes. [94] The aim of the patent Superfine regeneration powder compound geopolymer cementing material is to produce a geopolymer composite cementing material based on ultrafine regenerated powder from waste bricks and slag, and also includes a Portland cement clinker. The composite product thus combined with hydroxide and silicate has a strength of at least 32.5 and a 28-day compressive strength of not less than 40 MPa; in particular, the strength grade can reach 42.5 in the case of further addition of Portland cement clinker with a 28-day compressive strength of not less than 50 MPa. [95] The problem of integrating superfine dust is also raised by the patent Geopolymer gel material and application thereof, which aims to absorb construction waste dust in combination with the preparation of geopolymers. The precursor includes red brick earth, fly ash and slag, the activator is sodium silicate, sodium hydroxide or a mixture of both. [96]

In patent Waste concrete geopolymer and preparation method thereof, the results of the strengths that waste concrete-based geopolymers can achieve are evaluated. In particular, the compressive strength is high in the initial curing phase. After 3 days of curing treatment, the compressive strength of the waste concrete geopolymer reached 21MPa; after 28 days of curing treatment, the compressive strength of the waste concrete geopolymer reached 58 MPa, the flexural strength reached 4.8 MPa, high mechanical strength, good flexural performance and can be directly used as a construction material. [97]

Based on the results obtained on the patentscope platform, the search was repeated using the keyword "construction waste geopolymer". The resulting patents were 1128;

of these, excluding those resulting from the previous search and those already analysed on patentscope, 3 were closest to the subject matter. Patent “Waste clay brick base polymer building block and preparation method thereof” describes the preparation of polymer blocks based on brick waste, lime-based betonite and river sand. [98] The patented Recycled red brick micro-powder and mineral powder cooperative fly ash-based novel geopolymer mortar involves making a new geopolymer mortar based on red brick micro-powder fly ash, fly ash, mineral powder and fine aggregate, sodium hydroxide, sodium silicate and sodium carbonate. The resulting mortar achieves a 28-day compressive strength of 69.76 MPa and a 3-day compressive strength of 47.44 MPa. [99] The last precast analysed, Geopolymeric concrete using recycled aggregate from waste of construction and manufacturing method thereof, considers the use of concrete waste as recycled aggregate, where pre-treatment has been eliminated, to produce specimens with compressive strengths of 32.5 ~ 36.0 MPa. When the recycled aggregate is washed, a compressive strength of 38.2 MPa can be obtained. In addition, concrete produced from recycled geopolymer aggregate shows better acid resistance than cement concrete and no abnormalities were confirmed in 300 cycles of frost and thaw resistance tests and all results of the heavy metal leaching test were within the permitted leaching limit value. [100]

3.6. Partial conclusions of the chapter

The dissemination of the culture of eco-sustainable building cannot be separated from an in-depth knowledge of materials and construction techniques.

This "virtuous practice" of using secondary raw materials, in fact, makes it possible both to recover tradition in the rehabilitation of historic buildings and to design in a sustainable way. At the same time, the use of scraps from the ceramic industry or from demolition operations as alkaline-activated materials could encourage the use of geopolymer binders as an alternative to Portland cement-based ones in the production of concrete. However, many of the environmentally sustainable binder materials (cementitious or geopolymeric) are currently produced using fly ash, for which a significant reduction in availability is expected in the coming years, as many countries in Europe, including Italy, have committed to gradually reduce the use of carbon in electricity production [59]. Also LIFE projects on construction and demolition waste can give interesting suggestions and contributions in relation to collection, separation and recycling processes [101], especially to the decarbonisation of the construction sector by stimulating both product and process innovations in the recycling of construction and demolition waste.

The analysis of the state of the art has shown that high-quality recovery of construction and demolition waste is almost always possible through which secondary raw materials (SRMs) can be obtained, i.e. materials from recycling processes that can be fed back into the economic system for subsequent use in building components with high added value.

Unfortunately, the potential for recycling and re-use of construction and demolition waste is not yet adequately exploited, as a number of critical issues persist at different stages of the process.

What emerges is that, especially in Italy, the main problem, as far as technical and bureaucratic aspects are concerned, is represented by the specifications, both for public and private works; in many specifications, in fact, certain types of materials are specifically required and therefore it becomes impossible to use recycled materials or by-products. The obstacle, therefore, lies not only in the ability to recycle construction waste materials, but above all in the possible performance limits and quality characteristics of these resources, on which there is currently insufficient clarity. To ensure that what is now considered waste acquires its true value, it is essential to consider all the factors involved at the same time; the bureaucratic aspect should not be underestimated, as well as the respect for technical standards to guarantee performance characteristics, for environmental standards, by ensuring compliance and the absence of dangerous or potentially polluting substances, and for standards of suitability for use by subjecting all recovered by-products to CE marking procedures, as well as giving great importance to the management and planning of interventions. It is clear that it is necessary to implement the range of alternative solutions and their dissemination. The examples coming from the many projects analysed show the immense potential that the sector offers, which is why it is considered imperative from now on to refer to "surpluses" from building demolition and no longer to waste materials. Recently, the recycling of CDW has been extensively studied and reviewed [102-105]. The reported data indicate that CDW can be successfully used in the production of construction materials, resulting in products comparable to those produced from natural raw materials.

For example, cocciopesto waste (CBW) represents a valuable secondary resource for the production of concrete either as coarse or fine aggregate in concrete or as supplementary cementitious material [106, 107].

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CHAPTER 4 Methods

The experimental plan aimed at determining the feasibility of this new type of construction material obtained from construction and demolition waste is divided into eight phases:

PHASE 1: State of the art

PHASE 2: Definition of objectives

PHASE 3: Design of experimental activities

PHASE 4: Analysis and definition of materials

PHASE 5: Laboratory testing - Chemical analysis

PHASE 6: Laboratory tests - Physical and mechanical tests

PHASE 7: Data processing

PHASE 8: Proposals for technological applications

In the GANTT shown at the end of the description of the phases, the phases are identified with the temporal definition of the single ones; in the same way, the phases carried out at the DICEA (Department of Civil, Construction and Environmental Engineering), the phases carried out at the UPM (Universidad Politécnica de Madrid) and the phases developed simultaneously in both Universities are identified.

Phase 1: State of the art

The study of the state of the art in relation to the projects for the recycling of demolition materials is the first of the research activities carried out. This phase is essential and decisive because it gives the possibility to get in touch with everything related to the research topic, to analyse the problems encountered and to have fundamental starting points in order to carry on the research in an innovative way. The temporal development of this phase is constant throughout the entire research path, it is not only a starting point but it must be a continuous reference; the in-depth study of the state of the art sees the study of sources go in parallel with the participation in national and international congresses and conferences, the human contact and the direct sharing of research experiences, whether they are applicative or purely theoretical, provides that something extra that greatly influences the approach to the subject.

Phases 2 - 3: Definition of objectives and Design of experimental activities

Phase two, the definition of objectives, is a moment of analysis, synthesis and reflection on the data collected during phase one. Phase three, design of the experimental activities, is considered the natural consequence. These two phases took place both at the DICEA and at the UPM in order to define objectives, timing and methods in perfect synchrony with the needs of the research. Although they are temporally determined, as are all the others, these two phases were resumed from time to time according to the results obtained in the subsequent activities.

Phases 4 -5: Analysis and definition of materials and Laboratory testing - Chemical analysis

The activities of analysis and definition of the materials, as well as the chemical analysis in the laboratory, were carried out at the Department of Chemical Engineering, Materials and Industrial Production (DICMaPI) of the Polytechnic School and Basic Sciences of the University of Naples Federico II. This phase involves the study of the process parameters of the production of geopolymers starting from waste powders of:

- Bricks
- Tuff
- Cement Mortars

Phases 6 7: Laboratory tests - Physical and mechanical tests and Data processing

Phase 6 represents a scale-up of the mixtures obtained from the previous optimisation. It foresees the preparation of samples of real dimensions with which it is possible to carry out physical and mechanical tests in order to define and test their resistance and behaviour:

- Surface hardness
- Flexural strength
- Compressive strength
- Capillarity
- Absorption

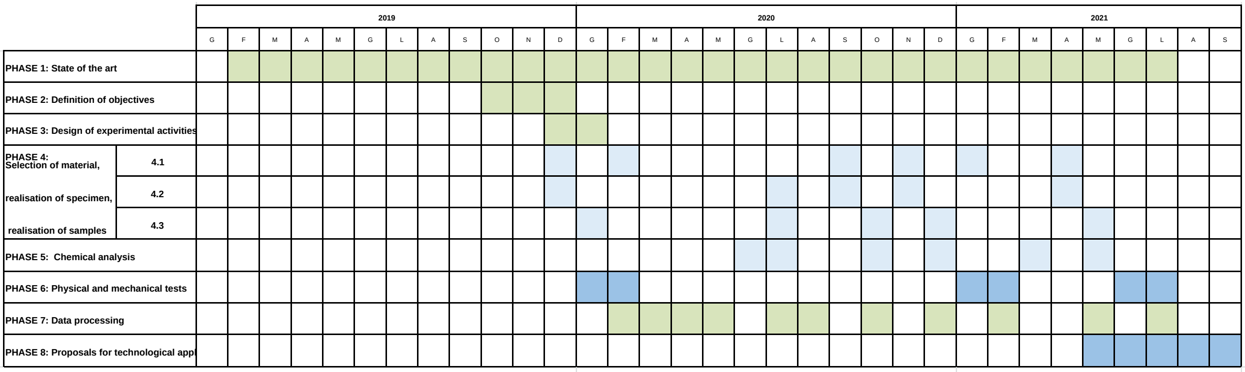
Mechanical tests were carried out at the TEMA laboratory of the Universidad Politécnica de Madrid.

The physical tests were carried out at the laboratory of the DICMaPI of the Polytechnical School and Basic Sciences of the University of Naples Federico II.

Phase 7 of Data Processing was carried out both at the DICMaPI of the Polytechnic School and Basic Sciences of the University of Naples Federico II, and at the UPM – Polytechnic University of Madrid; at the end of each cycle of tests and analyses, chemical, physical and mechanical tests were carried out. On the basis of the results obtained, further necessary tests were defined from time to time.

Phase 8: Proposals for technological applications

The final phase led to the definition of the possible technological applications of the new construction materials obtained; the evaluation took into account the characteristics of the materials obtained from the various mixtures, the costs and time required for preparation and the way in which the materials were applied.



Activities carried out at UPM and UNINA

Activities carried out at UPM

Activities carried out at UNINA

Table n.2 - GANTT of research phases

		2019											
		G	F	M	A	M	G	L	A	S	O	N	D
PHASE 1: State of the art													
PHASE 2: Definition of objectives													
PHASE 3: Design of experimental activities													
PHASE 4: Selection of material,	**4.1**												
realisation of specimen,	**4.2**												
realisation of samples	**4.3**												
PHASE 5: Chemical analysis													
PHASE 6: Physical and mechanical tests													
PHASE 7: Data processing													
PHASE 8: Proposals for technological appl													

Table n.3 - GANTT of research activities for the year 2019

		2020											
		G	F	M	A	M	G	L	A	S	O	N	D
PHASE 1: State of the art													
PHASE 2: Definition of objectives													
PHASE 3: Design of experimental activities													
PHASE 4: Selection of material,	**4.1**												
realisation of specimen,	**4.2**												
realisation of samples	**4.3**												
PHASE 5: Chemical analysis													
PHASE 6: Physical and mechanical tests													
PHASE 7: Data processing													
PHASE 8: Proposals for technological appl													

Table n.4 - GANTT of research activities for the year 2020

		2021								
		G	F	M	A	M	G	L	A	S
PHASE 1: State of the art										
PHASE 2: Definition of objectives										
PHASE 3: Design of experimental activities										
PHASE 4: Selection of material, realisation of specimen, realisation of samples	**4.1**									
	4.2									
	4.3									
PHASE 5: Chemical analysis										
PHASE 6: Physical and mechanical tests										
PHASE 7: Data processing										
PHASE 8: Proposals for technological appl										

Table n.5 - GANTT of research activities for the year 2021

4.1. Selection of materials

In response to what has been learned from professional experience and from studying the state of the art, it has been decided to refer to the materials most commonly used in the Campania area and more generally in the south of Italy, in the Madrilenian area and more generally in the world of construction; this type of evaluation has taken into account the materials characterised by traditional construction techniques, those proposed in more recent constructions and those coming from partial or total demolition or from activities related to extraordinary maintenance.

As mentioned in the details of the methodological phases, the materials selected were tuff, brick and cement mortars; all the materials used were secondary raw materials originating from demolition activities, either bought from dealers or collected directly on site.

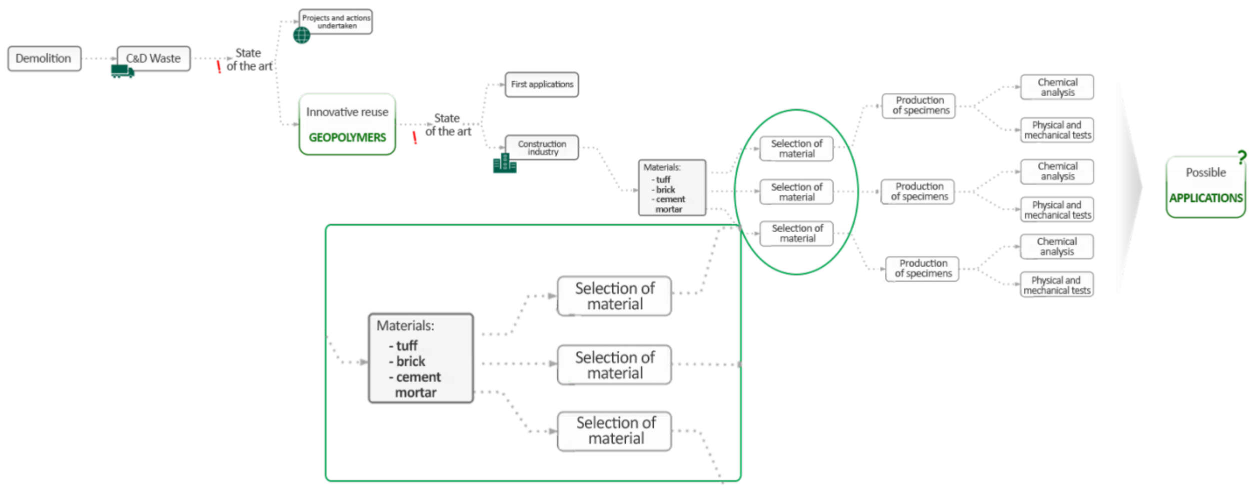


Figure n.10 - Flowchart of research activities related to the material selection phase

Figure n.11 - Secondary raw materials selected and ready for production of new materials

Figure n.12 - Raw materials divided by grain size

Tuff

The tuff used came from blocks of yellow Neapolitan tuff and blocks of Viterbo tuff, with dimensions of approximately 37x25x11 cm. The blocks used in the first phase were reduced to a smaller size by hand; the resulting material was then crushed and the powder sieved to select the correct particle size fraction; part of it was less than 0.3 mm and part ranged between 0.3 and 4 mm.

Figure n.13 - Tuff block

Figure n.14 - Tuff block size reduction activity

Figure n.15 - Crushing and collection of sieved material

Cement mortars

The cement-based material selected came from the cutting and demolition of the plaster on the façade of a building in the city of Naples. The material was already of a very fine grain size, which is why it was directly sieved in order to weigh the material to the desired fineness.

Figure n.16 - Material from the removal activities and first sieving phase

Figure n.17 - Particle size fractions

Bricks

The material for the production of the brick-based test specimens came from a dealer of materials that were recovered from construction and demolition activities. The original waste material had a different particle size composition from that which was selected for the experimental tests, so it was sieved and divided by the necessary weight amounts into the corresponding particle size fractions.

Figure n.18 - Brick waste

Figure n.19 - Granulometric fractions of bricks

Figure n.20 - Raw materials used as an aggregate

Alkaline solution

A sodium silicate (SS) solution (Na_2O 8.15%, SiO_2 27.40%) supplied by Prochin Italia S.r.L. (Caserta, Italy) with R (SiO_2/ Na_2O) equal to 3.3 and a 10 M sodium hydroxide solution, which was prepared by dissolving NaOH pellets (NaOH 98%, J.T. Baker) in double-distilled water, were then used as alkaline activators.

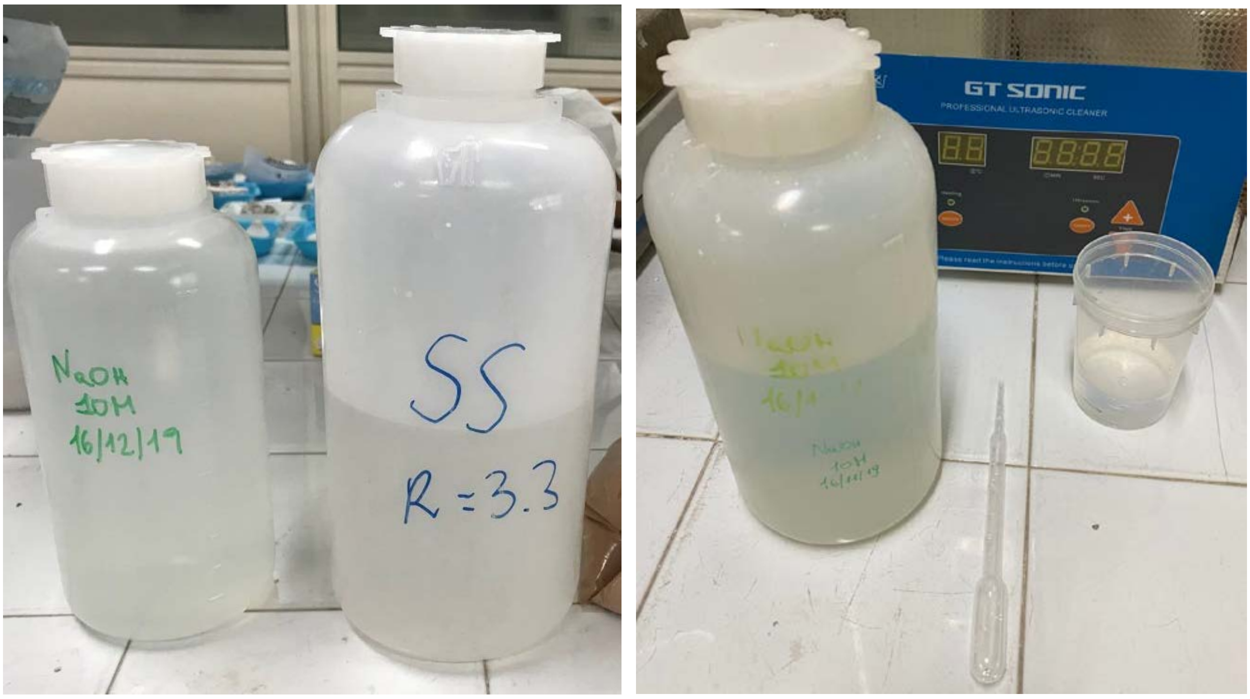


Figure n.21 - Solution of sodium silicate (SS) and 10M sodium hydroxide (NaOH)

4.2. Geopolymer mixtures

Based on the clayey nature of the waste [108], the preparation of the geopolymer was carried out following the prescription analysed and reported in previous articles [109, 110]. As a consequence, the powdered materials were previously dried mixed and homogenized, and then the activator solution was added.

The alkaline activator solution was prepared by mixing a sodium silicate (SS) solution with a 10M sodium hydroxide solution. The SS/N/binder ratio by weight was 1: 1: 3. The activator/binder ratio was 0.66.

Finally, the mixture was poured into special moulds and the samples were sealed and placed in an oven for 3 days at 60°C. Once they were consolidated, all samples were removed from the moulds and stored at room temperature until 28 days were reached as the ageing period before performing the experimental tests.

4.2.1 Assessment of the geopolymerisation capacity

This first phase consisted of evaluating the effective geopolymerisation of the selected mixture, based on the type of waste material that was chosen and its percentage, through the production of small cylindrical samples.

The mixture prepared according to the indications given in the previous paragraph was poured into cylindrical polyethylene moulds (diameter 30 mm; height 70 mm) where the samples were sealed and cured for 3 days at 60 °C in an oven. The aim is to perform a qualitative assessment of the degree of geopolymerisation by immersing the samples in double distilled water for 24 h at room temperature.

In order to further investigate the degree of geopolymerisation, infrared spectroscopy (FTIR) and thermal analyses were carried out. FTIR analyses were performed using a Nexus-Nicolet apparatus and selecting a resolution of 4 cm^{-1} for 32 scans from 4000 to 400 cm^{-1}. The FTIR spectra were collected in absorbance mode on transparent pellets obtained by dispersing the sample powders in KBr (2% wt/wt) on both the raw materials and the geopolymer samples produced. Thermal characterisation was performed by TGA/DTGA analysis (Netzsch, STA 409 PC Luxx) in the temperature range 20 - 1200 °C with a heating rate of 10 °C/min, under a nitrogen atmosphere.

Finally, morphological analyses were performed by scanning electron microscope, SEM (Cambridge S440). [111]

Figure n.22 - Geopolymerisation tests

4.2.2 Test specimens with C&D material

Once the evaluation of the geopolymerisation capacity was completed, a scale-up of the specimens that actually passed the first phase was carried out, and then the production of samples on which physical, chemical and mineralogical analyses and mechanical tests were performed, in order to determine the characteristics of the new material and hypothesise possible future applications. To achieve the objective of the study, a series of prismatic samples of 40x40x160mm were prepared, according to UNE EN1015-2:2012 [112] and UNE EN1015-11:2000 [113].

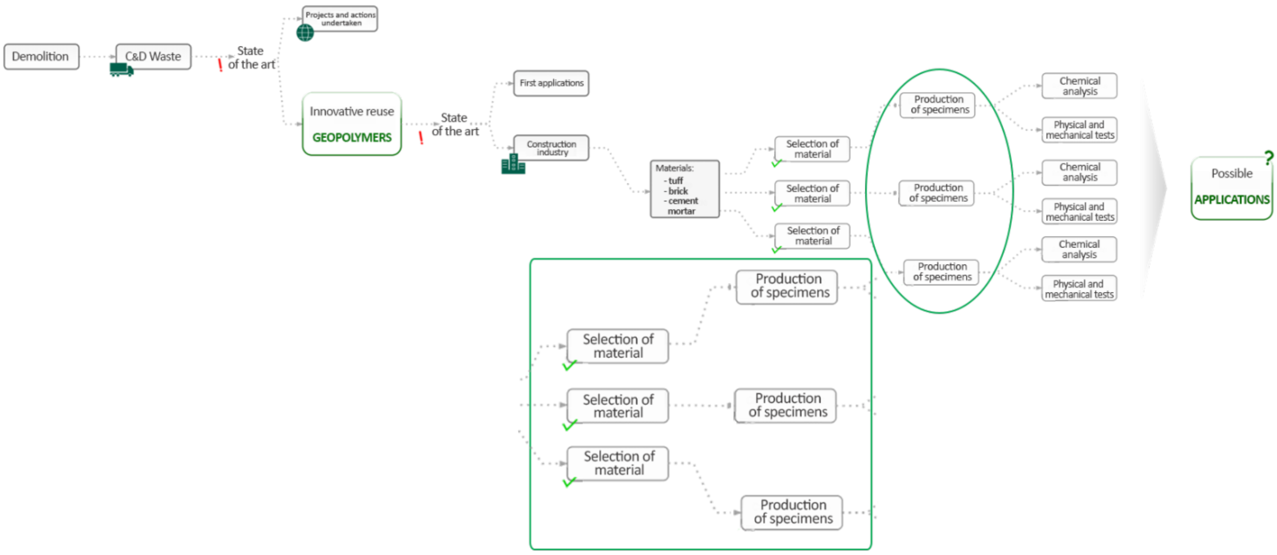


Figure n.23 - Flowchart of research activities related to the specimen production phase

Altogether thirty-six prisms measuring 40x40x160mm were produced from twelve selected mixtures. For each mixture, three samples were produced for mechanical testing.

For each mixture, a further series of cylindrical and cubic specimens was produced for the relevant physical tests.

In order to allow an easy identification of all samples, they were marked and numbered according to material, mixture and sample number.

The code CP refers to cocciopesto samples, the code C refers to cement waste, the code T refers to samples produced from tuff and the code M was used for samples containing a mix of the three materials used in the same proportions.

The values 100, 90, 80, refer to the percentage of material from construction and demolition activities used in the mixture; for the remaining percentage value, fly ash from electrical power plants (indicated by the initials FA) was used.

To the powdered material with a particle size of less than 0.3 mm, a fraction equal to 50% by weight of the same material with a particle size between 0.3 mm and 4 mm was added.

CP 100 + 50 1	C 100 + 50 1	T 100 + 50 1	M 100 + 50 1
CP 100 + 50 2	C 100 + 50 2	T 100 + 50 2	M 100 + 50 2
CP 100 + 50 3	C 100 + 50 3	T 100 + 50 3	M 100 + 50 3
CP 90 + 50 1	C 90 + 50 1	T 90 + 50 1	M 90 + 50 1
CP 90 + 50 2	C 90 + 50 2	T 90 + 50 2	M 90 + 50 2
CP 90 + 50 3	C 90 + 50 3	T 90 + 50 3	M 90 + 50 3
CP 80 + 50 1	C 80 + 50 1	T 80 + 50 1	M 80+50 1
CP 80 + 50 2	C 80 + 50 2	T 80 + 50 2	M 80 + 50 2
CP 80 + 50 3	C 80 + 50 3	T 80 + 50 3	M 80 + 50 3

Table n.6 - Summary table of prismatic samples produced

As shown in Table 6, they were therefore produced:

- n.3 samples with 100% of Cocciopesto (CP < 0,3mm) + 50% (CP > 0,3mm, < 4mm);
- n.3 samples with 90% of Cocciopesto (CP < 0,3mm) + 50% (CP > 0,3mm, < 4mm) and 10% of flyash;
- n.3 samples with 80% of Cocciopesto (CP < 0,3mm) + 50% (CP > 0,3mm, < 4mm) and 20% of flyash;
- n.3 samples with 100% of Cement (C < 0,3mm) + 50% (C > 0,3mm, < 4mm);
- n.3 samples with 90% of Cement (C < 0,3mm) + 50% (C > 0,3mm, < 4mm) and 10% of flyash;
- n.3 samples with 80% of Cement (C < 0,3mm) + 50% (C > 0,3mm, < 4mm) and 20% of flyash;
- n.3 samples with 100% of Tuff (T < 0,3mm) + 50% (T > 0,3mm, < 4mm);

- n.3 samples with 90% of Tuff (T < 0,3mm) + 50% (T > 0,3mm, < 4mm) and 10% of flyash;
- n.3 samples with 80% of Tuff (T < 0,3mm) + 50% (T > 0,3mm, < 4mm) and 20% of flyash;
- n.3 samples with 100% of Cocciopesto, Cement and Tuff (1/3 CP + 1/3 C + 1/3 T < 0,3mm) + 50% (1/3 CP + 1/3 C + 1/3 T > 0,3mm, < 4mm);
- n.3 samples with 90% of Cocciopesto, Cement and Tuff (1/3 CP + 1/3 C + 1/3 T < 0,3mm) + 50% (1/3 CP + 1/3 C + 1/3 T > 0,3mm, < 4mm) and 10% of flyash;
- n.3 samples with 90% of Cocciopesto, Cement and Tuff (1/3 CP + 1/3 C + 1/3 T < 0,3mm) + 50% (1/3 CP + 1/3 C + 1/3 T > 0,3mm, < 4mm) and 20% of flyash.

In addition, three prismatic study samples were preliminarily produced with a composition of 100% fine granulometry cocciopesto, and a further six samples of the selected mixture in the final phase as the optimal one, for a total of forty five prismatic samples.

Figure n.24 - Samples ready for shipment to the TEMA Lab of the UPM - Universidad Politécnica de Madrid

4.3 Chemical - mineralogical characterisation

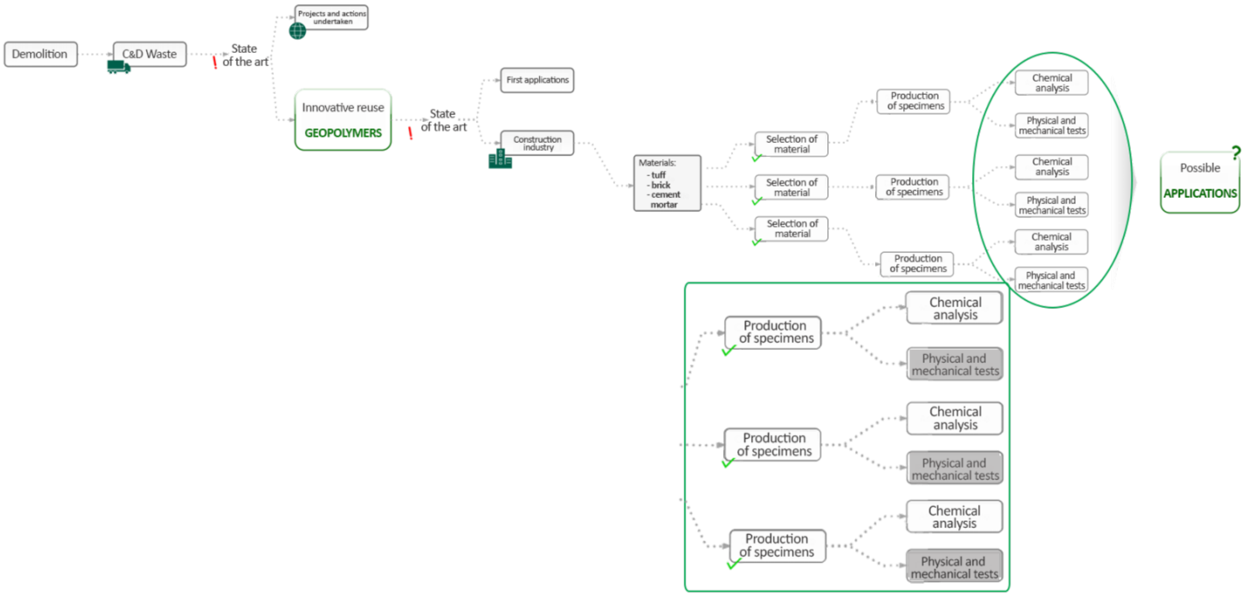


Figure n.25 - Flowchart of research activities related to the chemical analysis phase

The chemical composition was obtained according to the following procedure: a predetermined amount of sample was first calcined at 950 °C for 2 hours, then decomposed under microwave induced heating (Perkin-Elmer Multiwave 3000 furnace) into a standard solution obtained by mixing hydrochloric acid (37%, w/w), nitric acid (65%, w/w) and hydrofluoric acid (39.5%, w/w). A boric acid solution was then used to achieve fluoride complexation and the resulting solution was analysed using ICP-OES (Optima 2100 DV ICP-OES Inductively Coupled Plasma Spectrometer, Perkin Elmer).

The mineralogical composition of the samples was assessed by XRD analysis on powder samples using a Panalytical X'Pert Pro diffractometer equipped with a PixCel 1D detector (operating conditions: CuKα1/Kα2 radiation, 40 kV, 40 mA, range 2 from 5 to 80°, step size 0.0131° 2, counting time 40 s per step).

Figure n.26 - Preparation of samples for chemical and mineralogical characterisation

4.4. Physical characterisation

The laboratory tests for the physical characterisation were carried out at the materials laboratory of the DICMaPI of the University of Naples 'Federico'.

For the development of the tests, cubic and cylindrical samples were produced; before being subjected to the physical characterisation tests, all the samples were measured, weighed and dried in an oven at a temperature of about 60° until they reached a constant mass.

Figure n.27 - Mixtures poured into the cubic and cylindrical moulds for the production of physical test specimens and subsequently baked

4.4.1 Capillary rise test

Capillarity can be considered as one of the most significant mechanisms of water penetration in building materials and one of the main causes of building deterioration. For this reason, capillary rise tests were performed according to the European standard UNI EN 15801 [114] and the amount of water absorbed (Q) per unit area was evaluated as a function of time. The tests were carried out in triplicate on cubic (5 cm side) and on cylindrical samples. At the end of the test, the average value of the capillary absorption coefficient (CA, $mg/cm^2\ s^{-1/2}$) was determined. As for short-term times there is a fairly linear relationship between the adsorbed water (Q) and the square root of time, the CA value can be evaluated as the slope of the straight line in the first step (30 minutes) of the capillarity test [114]. A total of thirty-one samples were produced for the capillary rise test.

Relative to the cement waste:

- C 100 1 (100% waste material)
- C 100 2 (100% waste material)
- C 100 1 Cubic sample (100% waste material)
- C 100 2 Cubic sample (100% waste material)
- C 90 A (90% waste material and 10% flyash)
- C 90 B (90% waste material and 10% flyash)
- C 80 A (80% waste material and 20% flyash)
- C 80 A (80% spoilage and 20% flyash)
- C 10 A (10% waste material and 90% flyash)
- C 10 B (10% waste material and 90% flyash)

For cocciopesto waste:

- CP 100 A (100% waste material)
- CP 100 B (100% waste material)
- CP 100 C Cubic sample (100% waste material)
- CP 90 A (90% waste material and 10% flyash)
- CP 90 B (90% waste material and 10% flyash)
- CP 80 A (80% waste material and 20% flyash)
- CP 80 A (80% waste material and 10% flyash)
- CP 10 A Cubic sample (10% waste material and 90% flyash)
- CP 10 B Cubic sample (10% waste material and 90% flyash)

With regard to tuff residues:

- T 80 A (80% waste material and 20% flyash)
- T 80 B (80% waste material and 20% flyash)
- T 10 (10% waste material and 90% flyash)

For mixed waste:

- M 100 A Cubic sample (100% waste material)
- M 100 B Cubic sample (100% waste material)
- M 100 C Cubic sample (100% waste material)
- M 100 A (100% waste material)
- M 100 B (100% waste material)
- M 90 A (90% waste material and 10% flyash)
- M 90 B (90% waste material and 10% flyash)
- M 80 A (80% waste material and 20% flyash)
- M 80 B (80% waste material and 20% flyash)

Figure n.28 - Samples ready to be weighed and subjected to the capillary rise test

4.4.2 Absorption test

Open porosity and water absorption were evaluated according to the European standard [115]. In the first stage, the samples, after being dried at 60±5°C until a constant mass was reached, were immersed in water under vacuum at room temperature and left for two hours. Subsequently, each sample was weighed and the bulk density and hydrostatic weight evaluated. The pycnometer method was used after grinding the sample to a size of 0.063 mm to assess the closed porosity. The instrument used complied with ISO 3507. Each test was performed in triplicate and the results are determined from the average values. Water absorption by immersion was also evaluated, without placing the samples under vacuum, and by immersing the prismatic samples (4x4x16 cm3) in a water tank for 48 hours. The samples were first dried at 60±5°C to a constant mass, and then weighed before and after immersion, and finally the amount of water absorbed was deduced from the weight difference. [111]

Figure n.29 - Pycnometer method and hydrostatic weighing

4.5. Mechanical characterisation

For the mechanical strength tests, prismatic specimens were produced at the materials laboratory of the DICMaPI of the University of Naples 'Federico'; the specimens prepared were taken to the materials laboratory of the Departamento de construcciones arquitectónicas y su control of the Universidad Politécnica de Madrid for the laboratory tests to determine the mechanical characteristics.

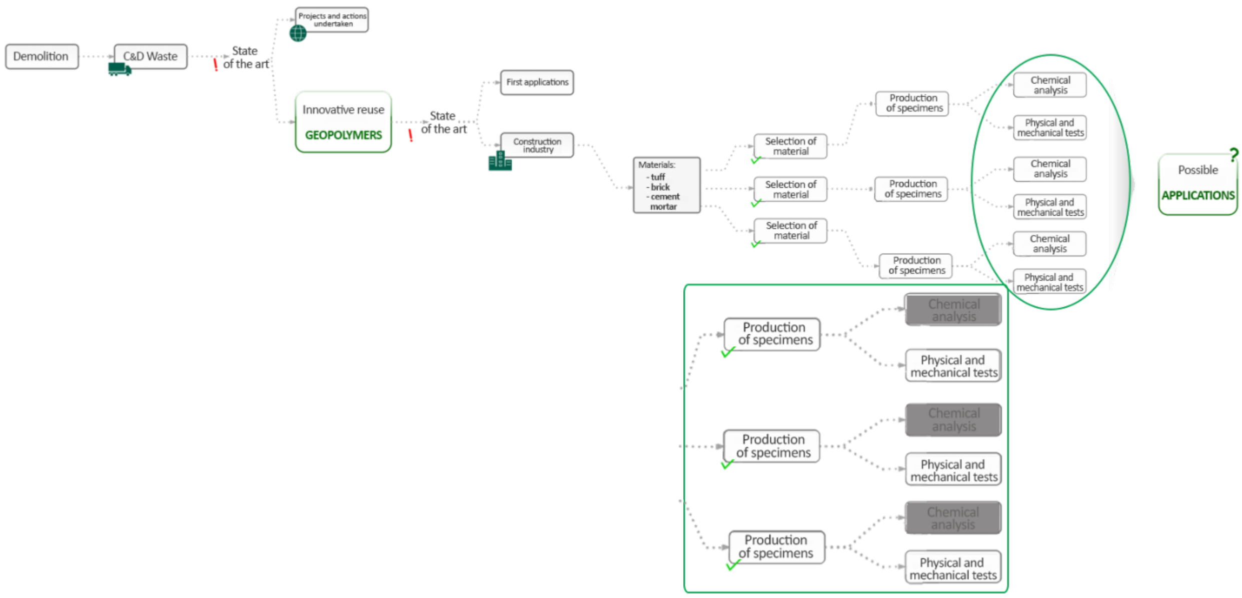


Figure n.30 - Flowchart of research activities related to the mechanical tests phase

4.5.1 Flexural strength

The flexural strength tests were performed according to UNE EN 13279-1:2009 [116] on prismatic specimens with dimensions 160 mm x 40 mm x 40 mm (Fig. 31). The testing machine used for the tests was the Ibertest. The specimens are placed centrally on the support rollers at 100 mm from each other. The load is applied until the specimens break, while the testing machine records the maximum load supported by the specimens expressed in newton. The flexural strength Rf is calculated using the following formula (1):

$$Rf = 0{,}00234 \times Fm \qquad (1)$$

where Rf is the flexural strength expressed in N/mm2 and Fm is the average breaking load of the values obtained, expressed in N.

Figure n.31 - Performing flexural strength tests on geopolymer samples

4.5.2 Compressive strength

The compressive strength tests were carried out following the same standard used for the flexural tests, EN 13279-1:2009 [116] (Fig. 32). The load is applied to the two broken portions of the specimens from the previous flexural strength tests.

The specimens are placed between two steel plates in such a way that the surfaces that come into contact with the plates have a cross-section of 40 mm x 40 mm. The test specimens are loaded until they break. The compressive strength Rc is calculated using the following formula (2):

$$Rc = Fc/1600 \quad (2)$$

where Rc is the compressive strength, Fc is the maximum load at break (N); and 1600 is the surface area (mm2) of the sample tested.

Figure 32 - Compressive strength tests on geopolymer samples

4.5.3 Surface resistance

The surface hardness was determined according to the standard EN 13279-2 [117]. The Shore D hardness test was carried out considering the hole that is produced on the sample under test, following the application of a determined force. Exerted on each sample, measured in Shore D units varying in a range from 0 (softest) to 100 (hardest).

In particular, the experimental tests were carried out on the two longitudinal sides of the prismatic samples (160 x 40 mm^2) (see Fig. 33).

Figure n.33 - Measurement of surface hardness using the Shore D test

4.6. Partial references of the chapter

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[117] EN 13279-2: 2014 - Gypsum binders and gypsum plasters - Part 2: Test methods. 2014

CHAPTER 5 Results

In this chapter the results of tests carried out at the materials laboratory of the DICMaPI of the University of Naples "Federico II" and at the TEMA Lab of the Universidad Politécnica of Madrid are reported and analysed. As will be seen in the course of the discussion, not all the mixtures have given appreciable results for the purposes of this line of research, for this reason it was decided to carry out the tests only for the mixtures found to be optimal, and to examine their results in depth.

5.1. Geopolymer mixture

Considering the innovative character of the research path undertaken, during the first phase of work several prisms (4x4x16 cm) were produced by hand from the fine powder of the cocciopesto waste. The objective was not only to ascertain the actual geopolymerisation capacity of the material but also, and above all, to start testing the properties and characteristics of the final product. So, the quantities of powdery waste and alkaline solution required for the production of three 100% CP prisms was defined, these quantities resulted as follows:

CP 100		
NaOH (10 M)	**SS (R=3)**	**CP (0,125-0,150 mm)**
336 g	336 g	1008 g

Table n.7 - Sample recipe CP 100

The mould was previously covered with acetate sheets to ensure a smooth surface finish. The three prisms (4x4x16 cm) thus produced were covered with film and placed inside the oven at 60°C for three days. At the end of the 72-hour "baking" period, the specimens were taken out of the oven and weighed. They were respectively:

- CP 100 1 = 446,14 g
- CP 100 2 = 434,34 g
- CP 100 3 = 471, 51 g

Figure n.34 - Hand production of the first 100% CP prismatic samples

Figure n. 35 - 100% CP prismatic samples

Figure n.36 - First 100% CP prismatic samples

The results of this mixture were satisfactory, especially in terms of its ability to geopolymerise; however, the intention to maximise the use of waste material and at the same time improve the mechanical properties led to a different optimisation of the recipe through the addition of a larger granulometry fraction to be used as aggregate and a percentage of another industrial waste material, the flyash. This optimisation will be reported extensively in the following paragraphs.

Subsequently, the mixing procedure was standardised and performed in a Hobart-type planetary mixer in order to obtain homogeneous mixtures ensuring an identical mixing capacity for all the samples produced. Furthermore, the use of such a machine, through the mass production of a larger quantity of material, not only reduced the packaging time of the samples but also led to a result as close as possible to the large-scale industrial production process which is the ultimate goal of this work. The mixing procedure is characterised by a very accurate timing: the first step is to mix the powdery material for about one minute, then the sodium hydroxide is added with a mixing period of two minutes, the same timing was adopted for the addition of the sodium silicate and finally the aggregate was added with a mixing period of about two or three minutes. The aggregate is added in the final stage of the mixture as it has been noted that following this sequence will enhance the workability of the mixture.

The choice of the granulometry fraction for the fine fraction of less than 0.3 mm to be used as a binder of the geopolymer and the gross fraction between 0.3 and 4 mm to be used as aggregate was determined by the results of the first samples produced, which were not optimal; in fact, the first samples produced with only one granulometry fraction between 0 and 4 mm were affected by the phenomenon of segregation in the fluid state and, consequently, characterised by a high degree of incoherence and fragility in the hardened state. These conditions resulted from a state of consolidation that had not been fully achieved.

In addition to the mixtures related to the individual waste materials selected, a mixed mixture was produced, in which both the binder and aggregate fractions are composed in equal parts of the three materials used and with the same weight determined for the other mixtures, in particular 750 g of aggregate divided into 250 g for each waste and 900 g of powder divided into the respective 300 g of residue.

Figure n.37 - Mixing procedure in the Hobart

Tuff

From a waste optimisation point of view, the results concerning tuff waste still leave some doubt as to the actual amount of material that can be reused for the production of new geopolymer materials. Furthermore, despite the evidence from the literature, the mixing and pouring process proved to be particularly difficult. In order to overcome this limitation of the mixture, water was used for wetting the pulverulent portion and the aggregate fraction; this solution made it possible to proceed easily with the packaging of the specimens. The first step was therefore to wet the yellow Neapolitan tuff, to which the flyash and the alkaline solution previously mixed were added.

The tuff-based cube (5x5) composed of 80% yellow Neapolitan tuff (TGN), 20% flyash and 50% aggregate of tuff from Viterbo (TV), is composed as follows:

T 80 + 50				
NaOH (10 M)	**SS (R=3)**	**TGN**	**FA**	**TV**
20 g	20 g	48 g	12 g	50 g

Table n.8 - sample recipe T 80 +50

Figure n.38 - Materials ready for mixing (tuff)

The following compositions were used to produce three prisms, two cubes and three cylinders:

T 100 + 50				
NaOH (10 M)	**SS (R=3)**	**TGN < 0,3 mm**	**FA**	**TV (0,3 -4 mm)**
300 g	300 g	900 g	/	750 g
T 90 + 50				
NaOH (10 M)	**SS (R=3)**	**TGN < 0,3 mm**	**FA**	**TV (0,3 -4 mm)**
300 g	300 g	810 g	90 g	750 g
T 80 + 50				
NaOH (10 M)	**SS (R=3)**	**TGN < 0,3 mm**	**FA**	**TV (0,3 -4 mm)**
300 g	300 g	720 g	180 g	750 g
T 10 + 50				
NaOH (10 M)	**SS (R=3)**	**TGN < 0,3 mm**	**FA**	**TV (0,3 -4 mm)**
300 g	300 g	90 g	810 g	750 g

Table n. 9 - Sample recipe based on tuff

Cement mortars

The geopolymer mixtures produced from the demolition waste, composed as follows, were sufficient for the construction of three prisms (4x4x16 cm) and three cubes (5x5 cm).

		C 100 + 50		
NaOH (10 M)	**SS (R=3)**	**C < 0,3 mm**	**FA**	**C (0,3 -4 mm)**
300 g	300 g	900 g	/	750 g
		C 90 + 50		
NaOH (10 M)	**SS (R=3)**	**C < 0,3 mm**	**FA**	**C (0,3 -4 mm)**
300 g	300 g	810 g	90 g	750 g
		C 80 + 50		
NaOH (10 M)	**SS (R=3)**	**C < 0,3 mm**	**FA**	**C (0,3 -4 mm)**
300 g	300 g	720 g	180 g	750 g
		C 10 + 50		
NaOH (10 M)	**SS (R=3)**	**C < 0,3 mm**	**FA**	**C (0,3 -4 mm)**
300 g	300 g	90 g	810 g	750 g

Table n.10 - Sample recipe based on cement waste

Figure n.39 - Ready-mixed materials (cement)

Brick

The amount of material used to ensure the production of three prisms, two cubes and one cylinder, for each type of mixture was as follows:

		CP 100 + 50		
NaOH (10 M)	**SS (R=3)**	**CP < 0,3 mm**	**FA**	**CP (0,3 -4 mm)**
300 g	300 g	900 g	/	750 g
		CP 90 + 50		
NaOH (10 M)	**SS (R=3)**	**CP < 0,3 mm**	**FA**	**CP (0,3 -4 mm)**
300 g	300 g	810 g	90 g	750 g
		CP 80 + 50		
NaOH (10 M)	**SS (R=3)**	**CP < 0,3 mm**	**FA**	**CP (0,3 -4 mm)**
300 g	300 g	720 g	180 g	750 g
		CP 10 + 50		
NaOH (10 M)	**SS (R=3)**	**CP < 0,3 mm**	**FA**	**CP (0,3 -4 mm)**
300 g	300 g	90 g	810 g	750 g

Table n. 11 - Sample recipe based on brick wastes

Figure n.40 - Ready-mixed materials (brick)

The mix produced with the 100% with 50% of aggregate was difficult to pour into the moulds; nevertheless a good level of compaction was achieved.

5.1.1 Results of the geopolymerisation capacity

The qualitative assessment of the degree of geopolymerisation is carried out by immersing the samples in double distilled water for 24 h at room temperature. In fact, if the geocomposites are intact after the immersion period, the formation of the geopolymer gel can be considered successfully achieved because the water absorption can be used as an indicator of the degree of reaction of the geopolymer [118]. The first tests related to the evaluation of the geopolymerisation capacity were performed through the production of three cylinders; the first mixtures produced were based on 100% Flyash (to be used as a reference), 100% Cocciopesto and a third mixture consisting of 50% Flyash and 50% Cocciopesto, according to the following quantities:

FA 100			
NaOH (10 M)	**SS (R=3)**	**/**	**FA**
16 g	16 g	/	48 g
CP 100			
NaOH (10 M)	**SS (R=3)**	**CP (0,125 -0,150 mm)**	**FA**
16 g	16 g	48 g	/
FA 50 + CP 50			
NaOH (10 M)	**SS (R=3)**	**CP (0,125 -0,150 mm)**	**FA**
16 g	16 g	24 g	24 g

Table n.12 - Composition of geopolymerisation cylinders

The mixtures were poured into closed cylinders and placed in an oven at 60°C for three days; at the end of the three days, they were immersed in double distilled water for 24 hours. The results of the first test were extremely satisfactory for all three mixtures. For this reason, the test was carried out for all the mixtures selected in the present work.

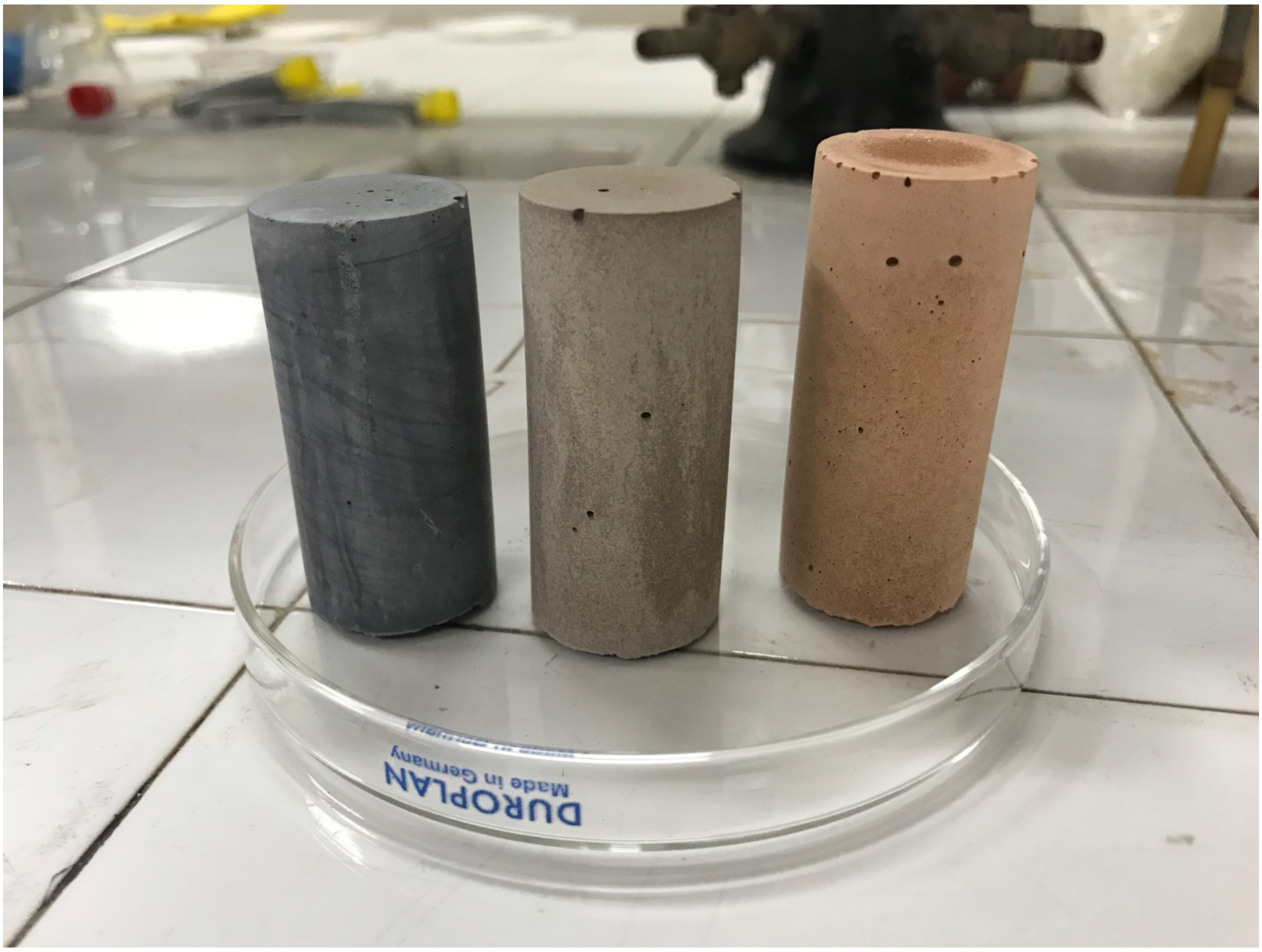
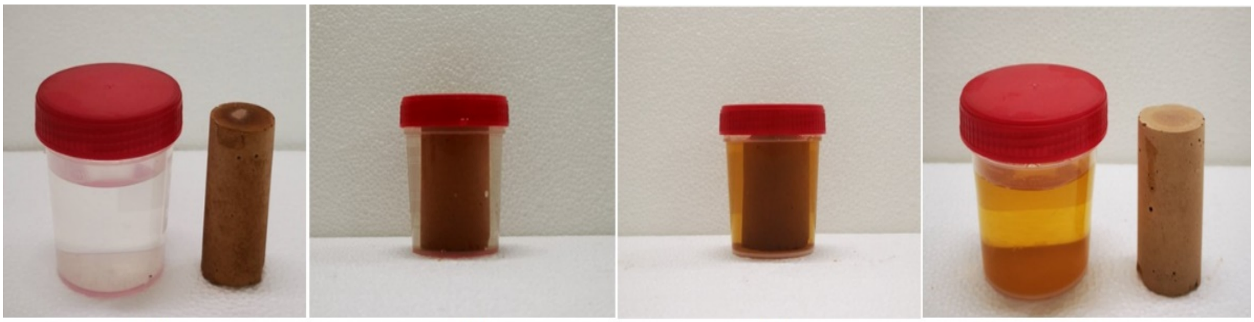


Figure n. 41 - Geopolymerisation tests (100% flyash, 50% cocciopesto/50% flyash, 100% cocciopesto)

Pictures of some of the samples subjected to the immersion process are shown below.

CP 100



(a) (b) (c) (d)

Figure n.42 - Geopolymer sample before (a), during (b), (c) and after immersion (d) in double distilled water for 24 hours

T 100, T 90 e T 80

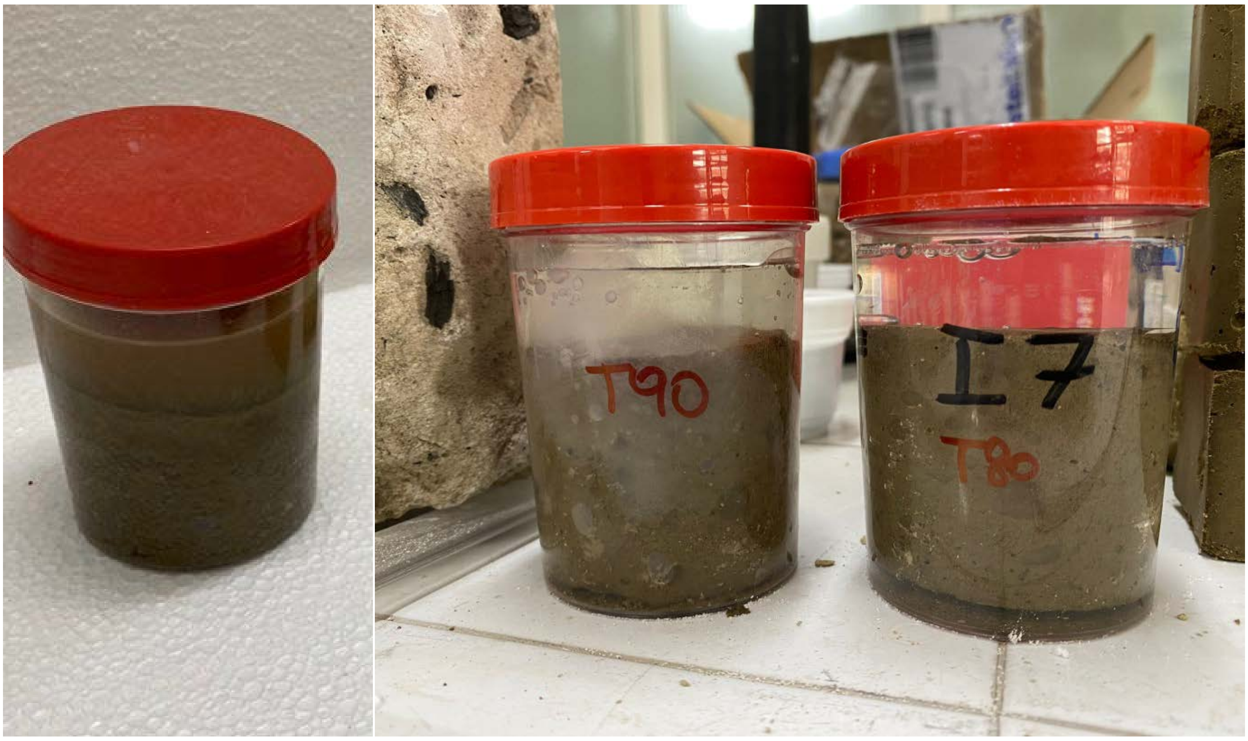


Figure n.43 - Geopolymer samples of T 100, T 90 and T80

The geopolymerisation test for the samples produced from tuff gave negative results in the case of the T 100 and T 90 samples; for this reason, the prisms produced with the T 80 mixture are the only ones to be subjected to the physical and mechanical tests, as will be seen in the following paragraphs.

Since the brick-based mixture produced the most satisfactory results, FTIR was used to verify the degree of geopolymerisation of the geocomposites [119-121]. The geopolymers produced from earthenware are mainly themselves amorphous aluminosilicates, which is why they show FTIR spectra (Fig. 43, solid line) characterised by the typical absorption bands of Si-O-Si and Si-O-Al bonds (absorption range 600-800 cm-1). The bands at 3450 cm-1 and 1647 cm-1, associated with O-H stretching and bending, are related to bound water molecules that are absorbed at the surface or trapped in the large cavities of the molecular structure [120,122]. The intensity of these bands is higher in the FTIR spectra of geopolymers, indicating both a higher degree of adsorption of water molecules in their bulk and the occurrence of a geopolymerisation reaction of the raw materials into geopolymer pastes [123]. A further confirmation of the presence of the aluminosilicate species typical of geopolymer composites in the samples produced with brick is found in the TGA curve and the XRD spectrum. In particular, the XRD spectrum (Figure 44) showed the appearance of peaks associated with the presence of Phillipsite ($(Ca,Na_2,K_2)3Al_6Si_{10}O_{32}$-$12H_2O$), only aluminosilicate crystalline phase, while the presence of other amorphous geopolymer phases is linked to the gradual weight loss that was detected between 250° and 600°C in the TGA curve.

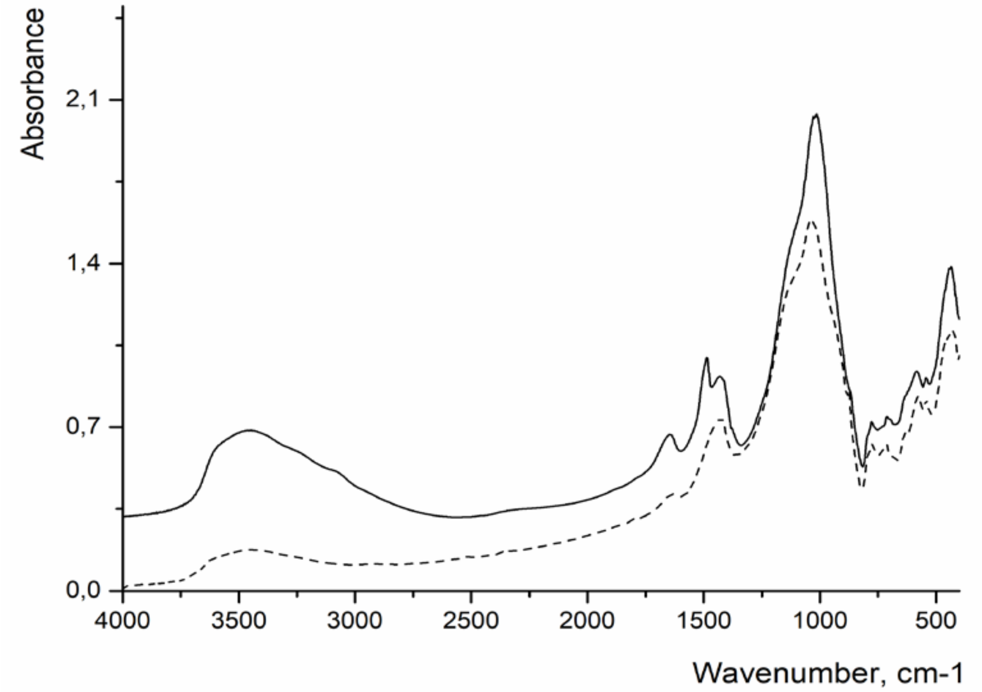


Figure n.44 - FTIR spectra of brick waste (dotted line) and geopolymer (solid line)

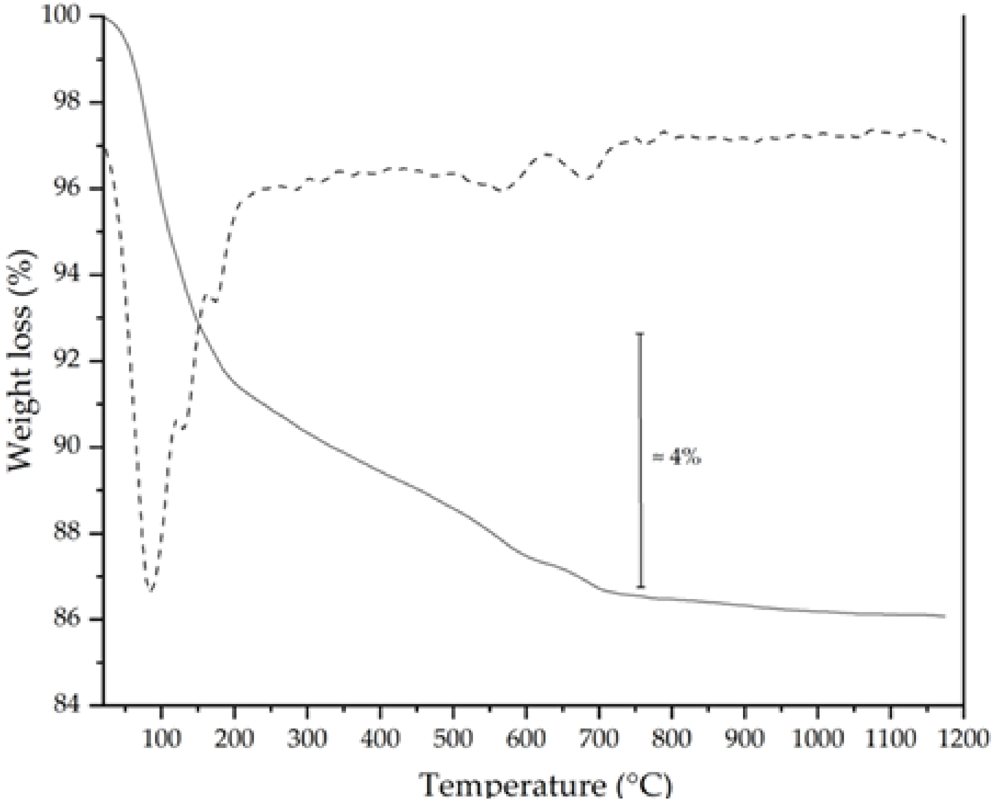


Figure n.45 - TGA (continuous line) and DTG curve (dashed line)

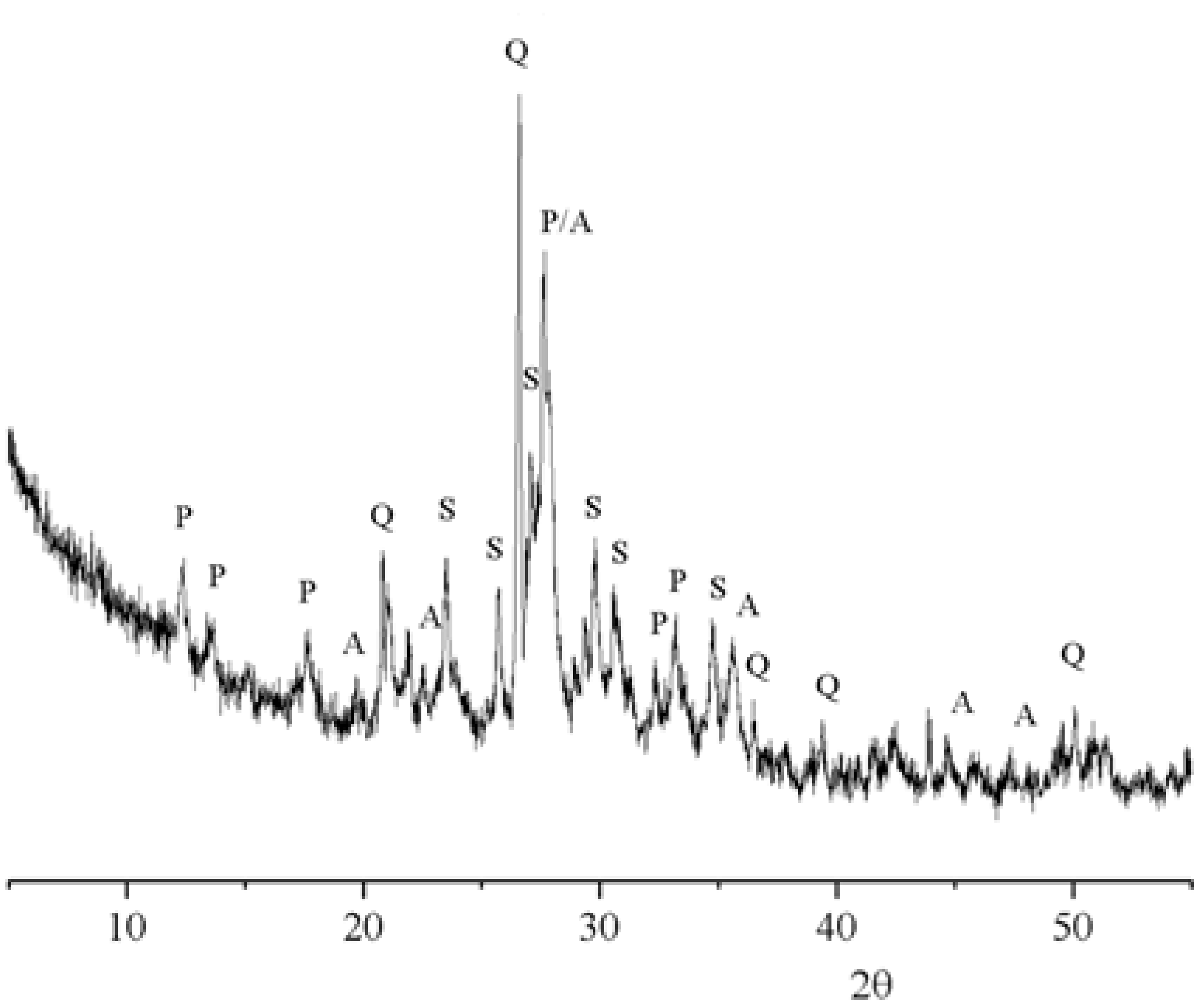


Figure n.46 - XRD spectrum of sample CP, Q = Quartz, P = Phillipsite, S = Sanidine, A= Albite

Finally, the following images present the results of SEM investigations at different magnifications (from 50 to 3000X) on geopolymers produced from brick waste. The EDX spectra confirmed the silico-aluminate nature of the geopolymer product. The CP-based sample was characterised by a porous and heterogeneous matrix with some unreacted particles (500X magnification). At higher magnifications (1500X and 3000X), the amorphous structure of the geopolymer structure was evident.

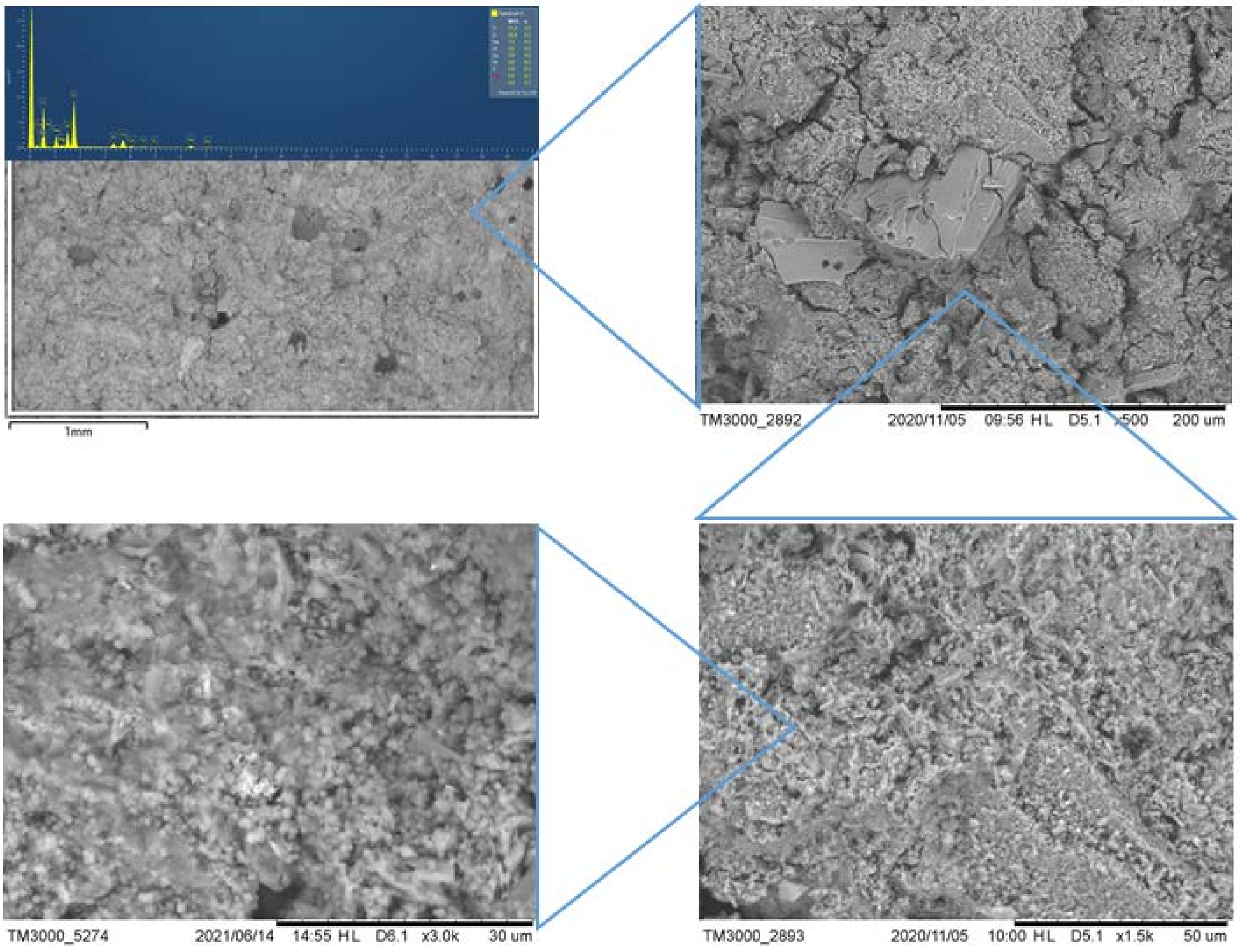


Figure n.47 - SEM images of the geopolymer structure at different magnifications. From left to right in a clockwise direction we find: 50X, 500X, 1500X, 3000X

5.1.2 Samples produced with C&D waste materials

In this paragraph the results of the preparation of all the samples produced for both physical and mechanical tests are reported, divided by type of material. The production phase of the samples involved the production of prismatic (4x4x16 cm), cubic and cylindrical specimens. All the samples were produced at the materials laboratory of the DICMaPI of the University of Naples "Federico II". After the production, the cubic and cylindrical samples were stored at the same department waiting to be subjected to physical tests; the prismatic samples were taken to the TEMA Lab of the Departamento de construcciones arquitectónicas y su control of the Escuela Técnica Superior de Edificacion of the Universidad Politécnica de Madrid.

In particular, a series of images of the finished products of the project is shown. All the following samples, as mentioned, were baked for three days at a temperature of 60 °C.

Figure n.48 - Samples produced for physical properties characterisation tests

Tuff

Figure n.49 - Tuff samples for physical properties characterisation tests

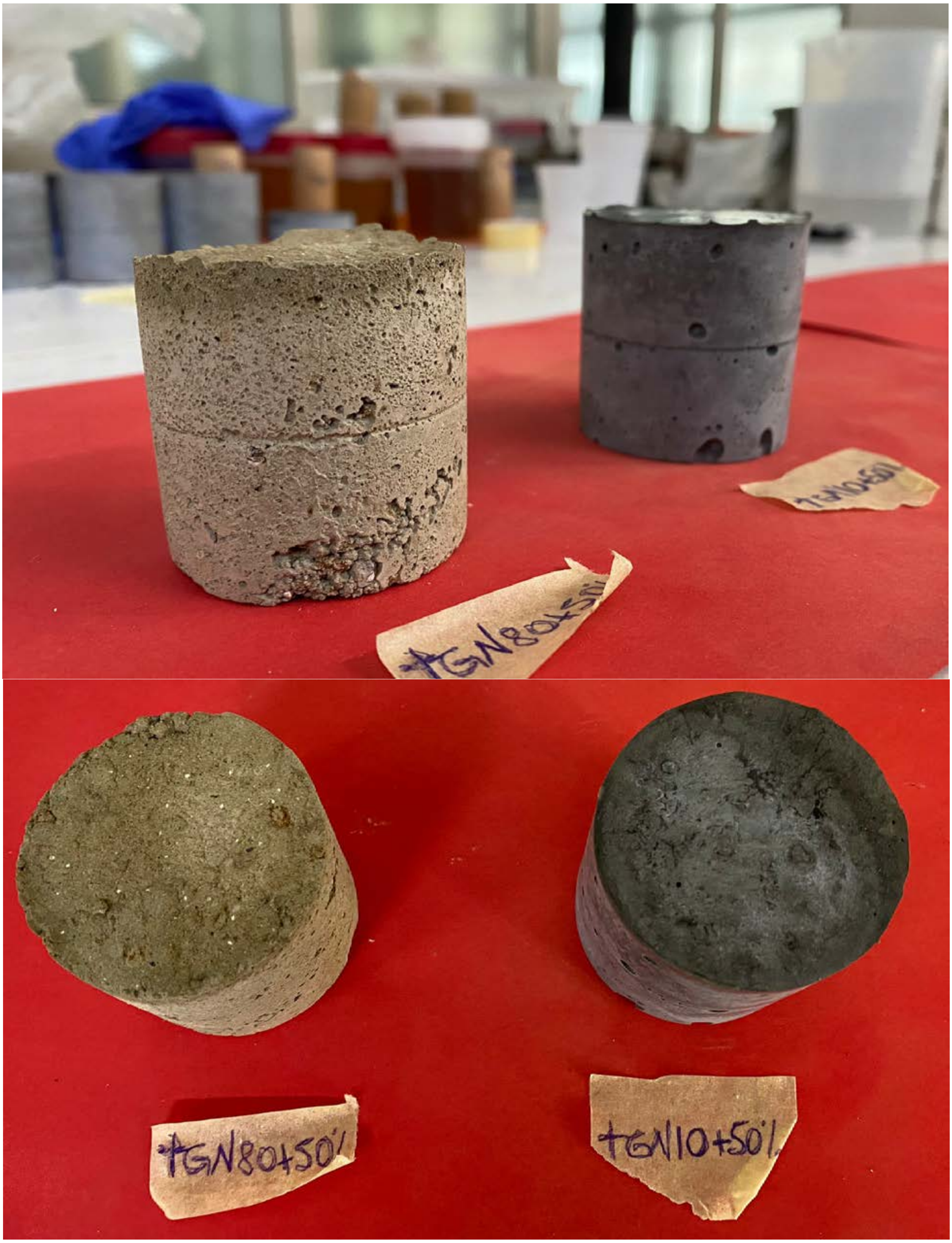


Figure n.50 - Cylindrical tuff specimens for physical properties characterisation tests

Figure n. 51 - Prismatic tuff samples

Figure n.52 - Prismatic samples of tuff according to 100% and 90% composition

It is important to note that with regard to the samples produced from tuff, the mixture made from 100% of the material did not produce positive results in the geopolymerisation test; therefore the prismatic samples for the mechanical tests and the cylindrical and cubic samples for the physical characterisation tests were not produced. Figure n.51 shows the percentages of 100%, 90% and 80%. In particular, in figure n.52 it is possible to note both the part dissolved in bidistilled water of the cylindrical sample produced to evaluate the geopolymerisation capacity of the mixture made with 100% yellow Neapolitan tuff residues, and the samples produced with 90% tuff.

The mixture made with the 90% of yellow Neapolitan tuff, 10% of flyash and 50% of tuff aggregate, managed to solidify during the curing phase, despite the fact that when the samples were extracted from the moulds, they broke naturally. In fact, this behaviour is not surprising considering that already during the geopolymerisation test; the cylinder immersed in double distilled water had left some sediment on the surface of the test tube after 24 hours.

Figure n.53 - Detail of prismatic samples of 90% mixture tuff

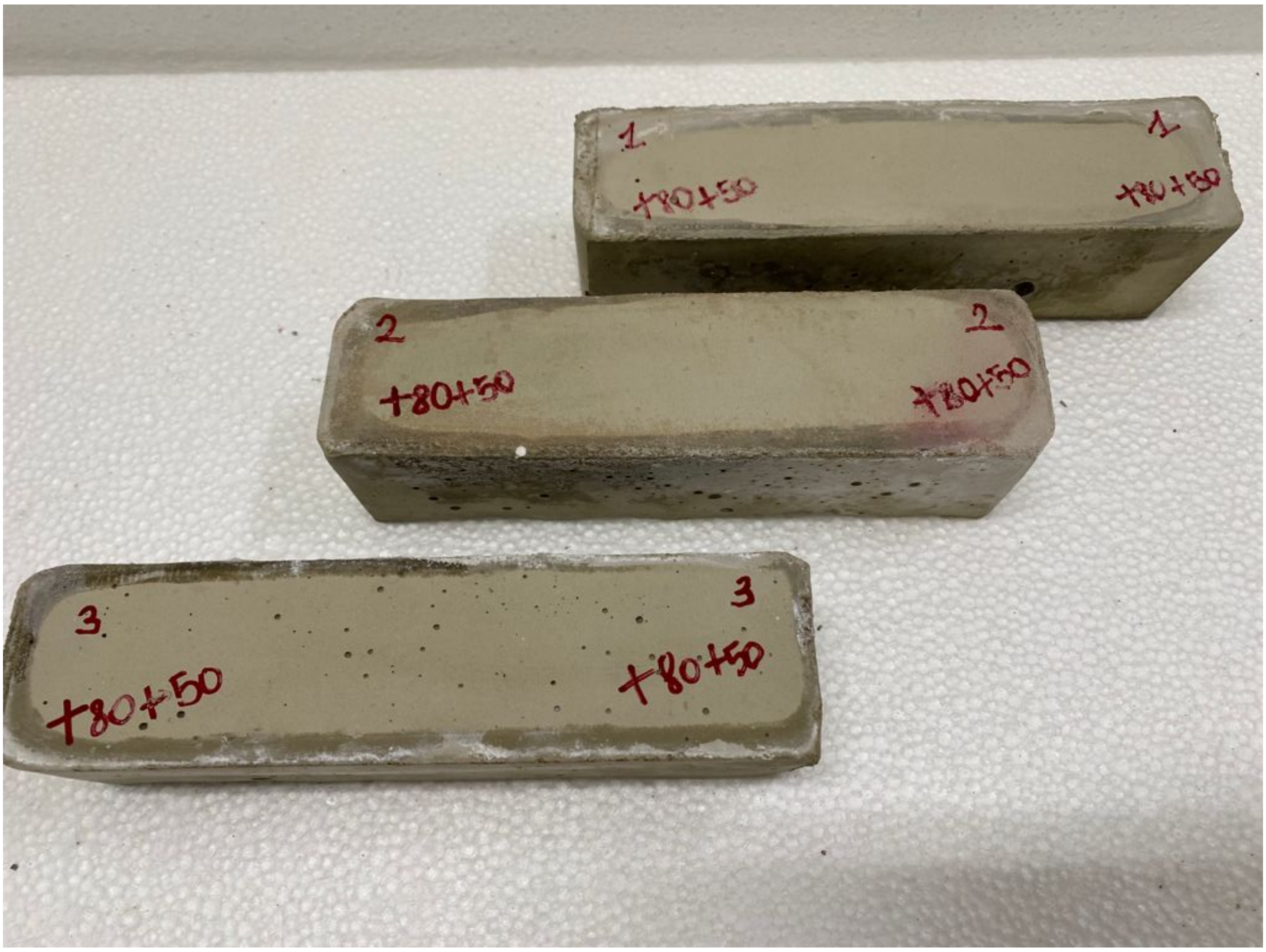


Figure n.54 - Prismatic samples of tuff according to composition 100% and 90%.

Cement mortar

Figure n.55 - Cylindrical cement-based test specimens according to 10% composition

Figure n.56 - Cubic and cylindrical cement-based test specimens according to 100% composition

Figure n.57 - Cylindrical test pieces produced from cement residues from the demolition activity

Figure 58 - Cylindrical cement-based test specimens of 80% and 90% mixtures

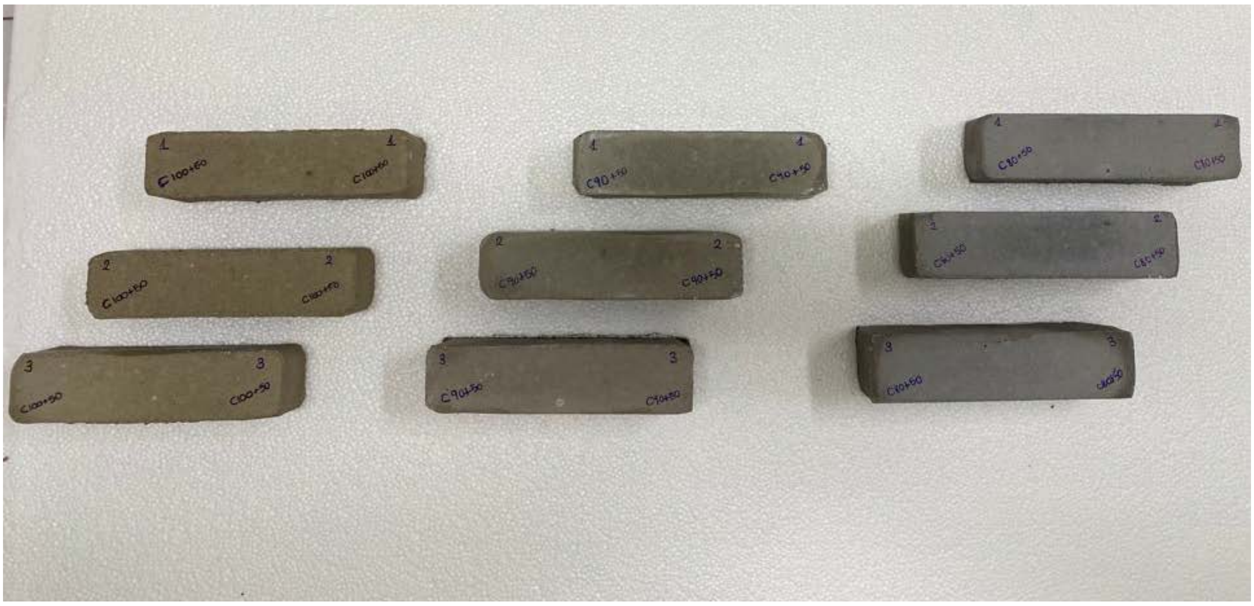


Figure n.59 - Prismatic samples of cement-based mixtures

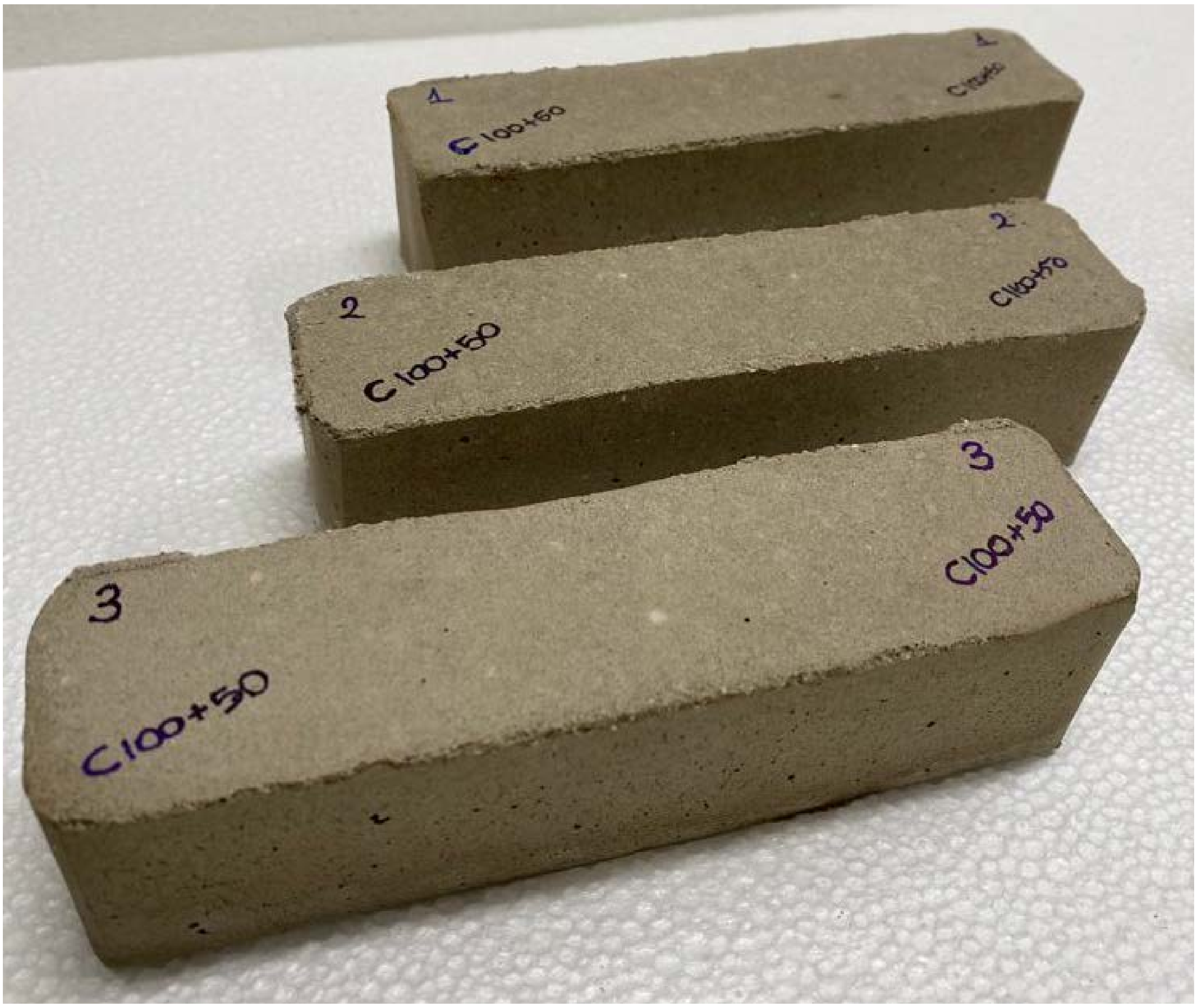


Figure n.60 - Prismatic samples of cement-based mixtures (percentage 100%)

Figure n.61 - Prismatic samples of cement-based mixtures (percentage 90%)

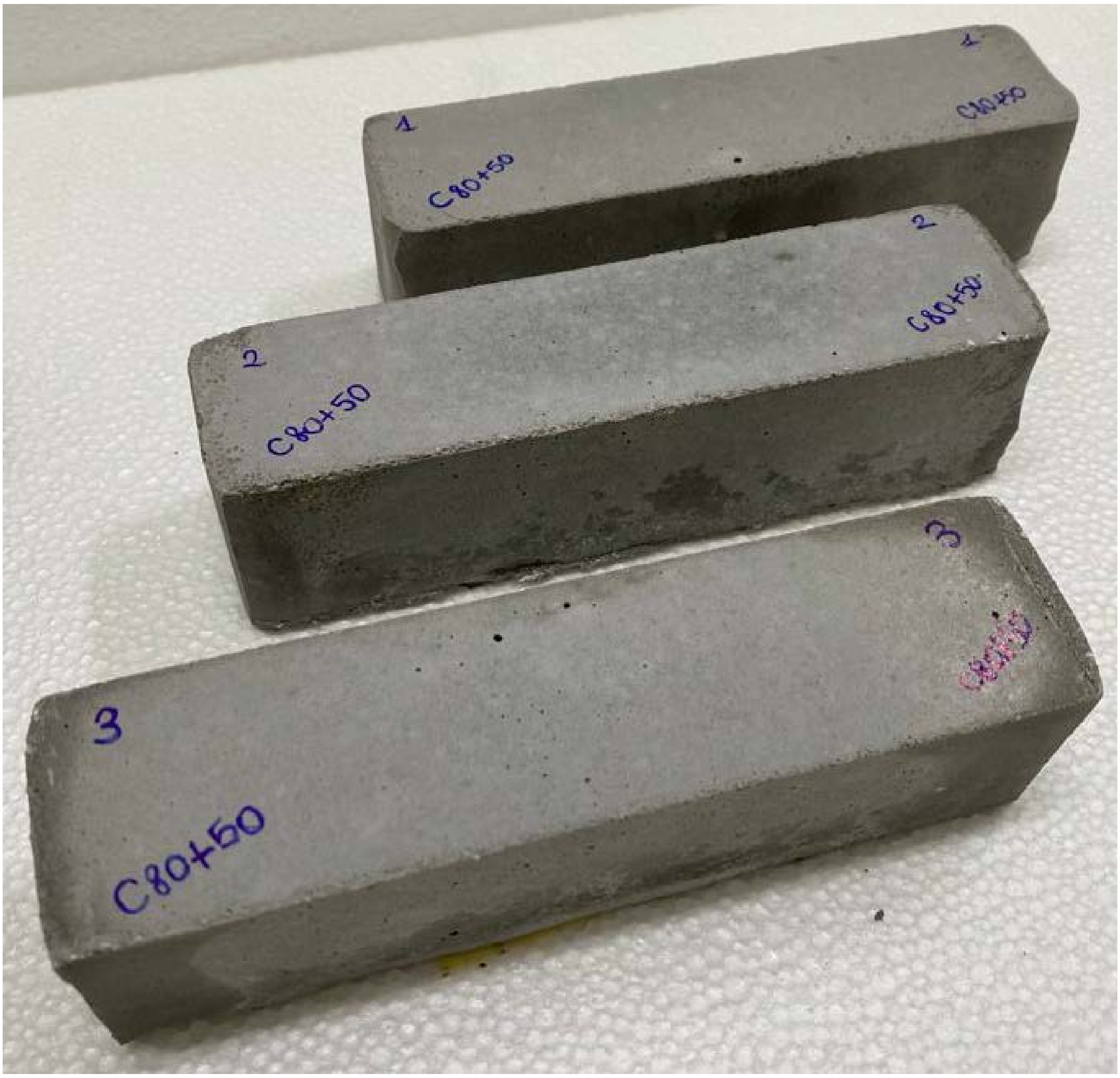


Figure n.62 - Prismatic samples of cement-based mixtures (percentage 80%)

Brick

Figure n.63 - Cubic and cylindrical brick-based test specimens containing 100% demolition waste

Figure n.64 - Cubic and cylindrical brick-based test specimens

Figure n.65 - Cubic samples containing 10% demolition waste and 90% flyash

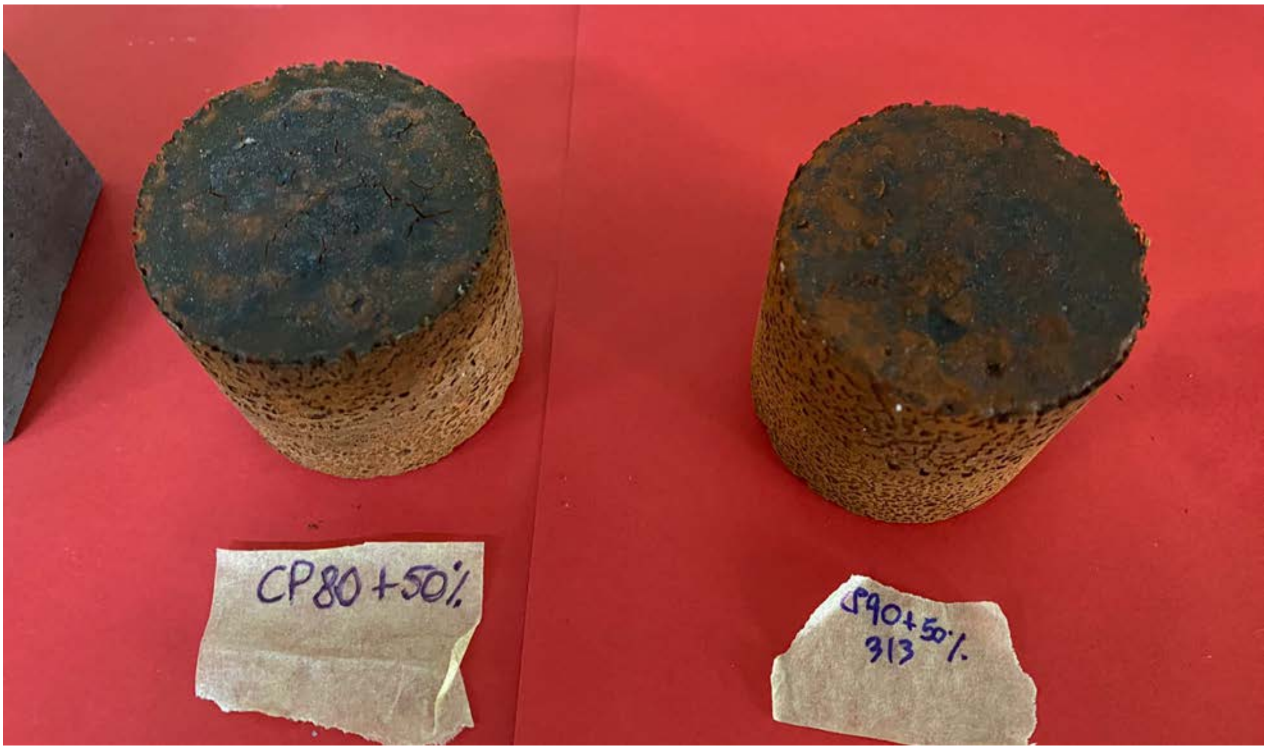


Figure n.66 - Cylindrical test pieces for mixtures with 80% and 90% brick

Figure n.67 - Prismatic samples of brick-based mixtures

Figure n.68 - Prismatic samples for brick-based mixtures (percentage 100%)

Figure n.69 - Prismatic samples for brick-based mixtures (percentage 90%)

Figure n.70 - Prismatic samples for brick-based mixtures (percentage 80%)

Mixed Tuff-Cement-Brick

Figure n.71 - Cubic and cylindrical specimens with 100% mixed mixture

Figure n.72 - Prismatic samples of mixtures based on demolition mixture

Figure n.73 - Prismatic samples of demolition mixture (percentage 100%)

Figure n.74 - Prismatic samples of demolition mixture (percentage 90%)

Figure n.75 - Prismatic samples of demolition mixture (percentage 80%)

At the end of the preparation and the production of the samples, all of them were measured and weighed in order to be able to proceed with the experimental laboratory activities related to the physical and mechanical tests; in the following paragraphs the weights of all the samples will be reported.

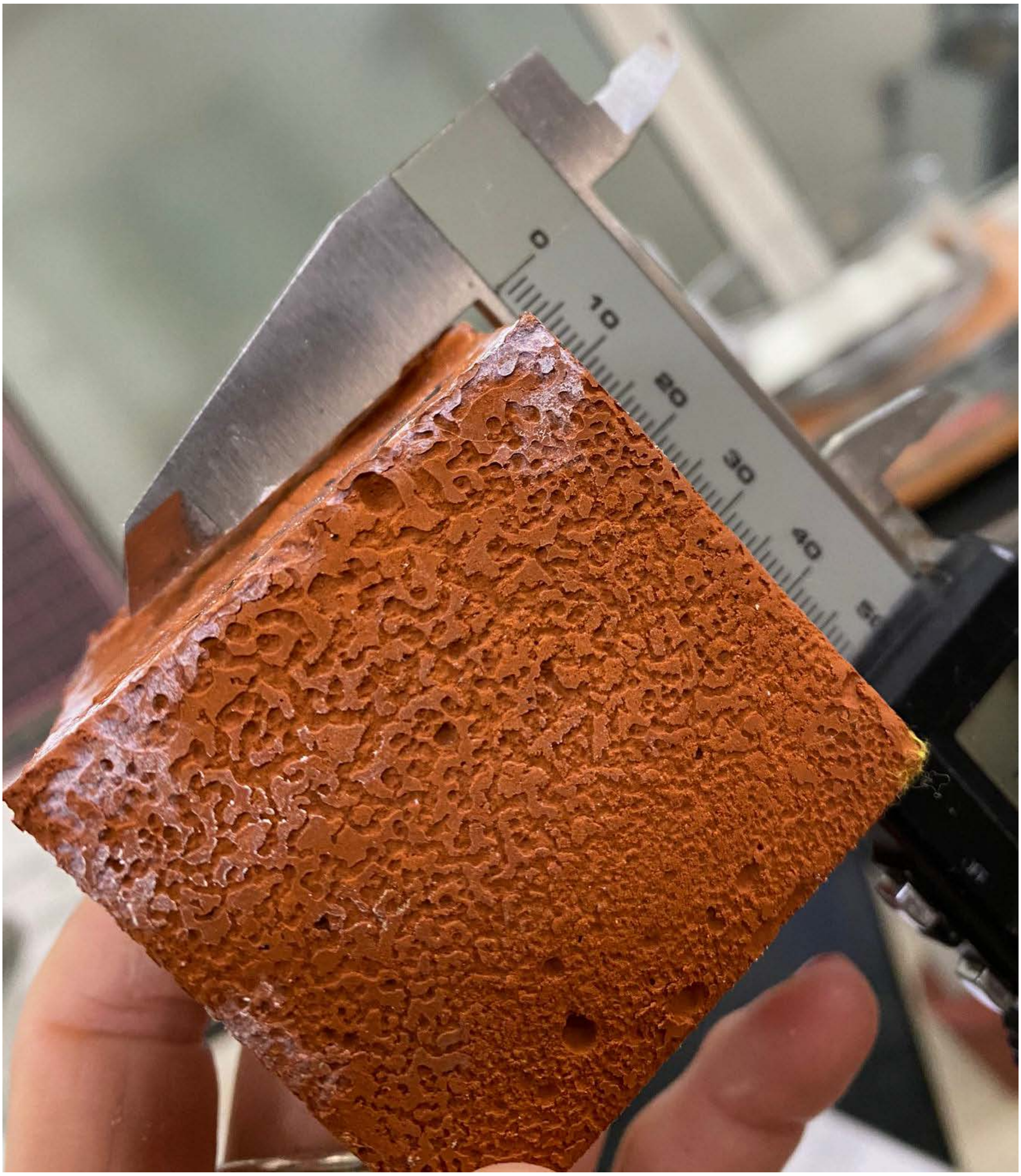


Figure n.76 - Sample measured before testing

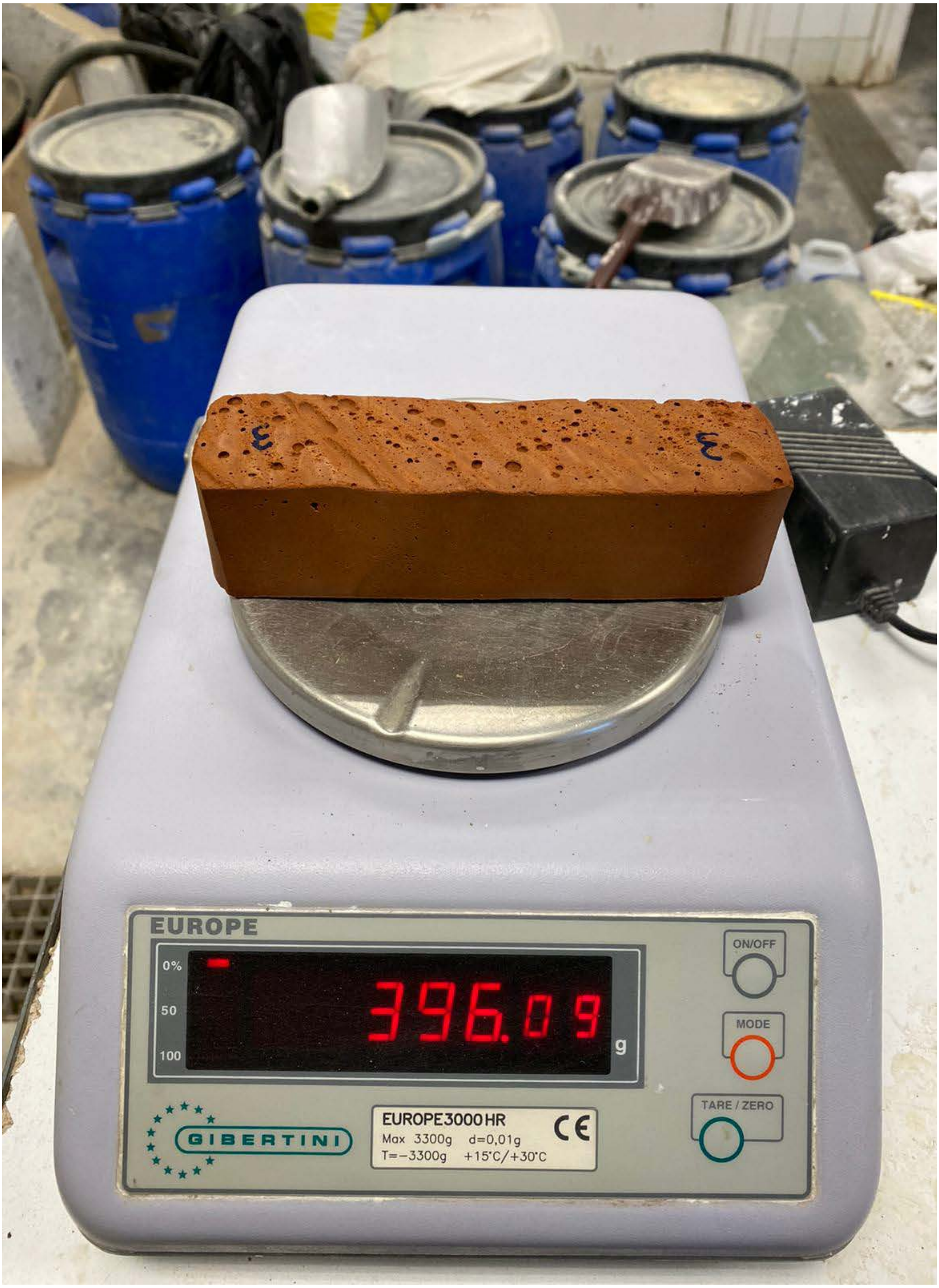


Figure n.77 - Sample weighed before testing

5.2. Results of the chemical - mineralogical characterisation

The material that gave the most satisfactory results was the brick and indeed the chemical and mineralogical composition, shown in Table 7, confirmed the clayey nature of the sample with a SiO_2/Al_2O_3 ratio of 1.5 and a significant amount of alkaline oxides and alkaline-earth.

Major elements (wt%)						
SiO_2	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	CaO
47,90	31,82	2,99	4,14	3,75	3,59	4,52
XRD mineralogical phases						
Quartz	Calcium Carbonate		Sanidine		Albite	

Table n.13 - Chemical and mineralogical composition of brick wastes

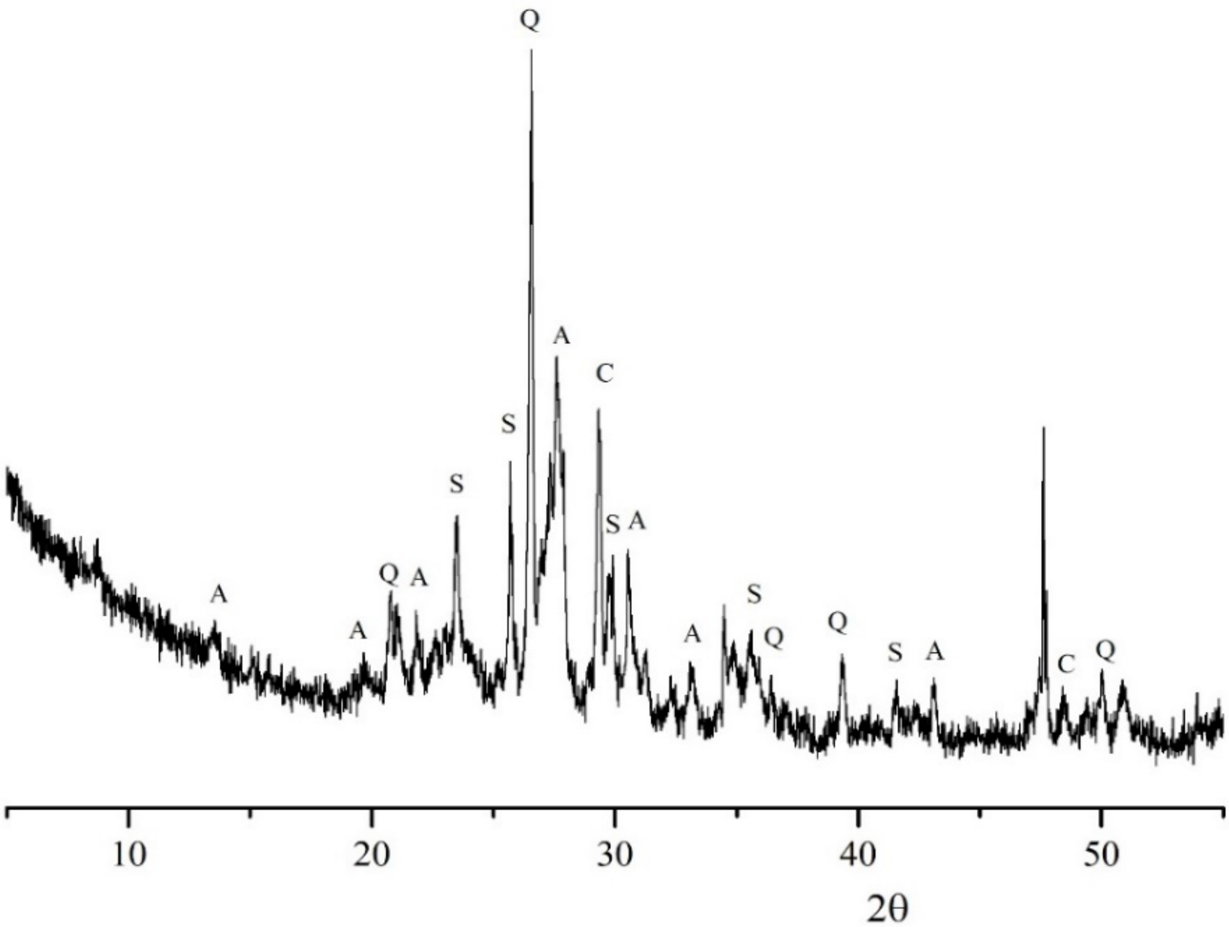


Figure n.78 - XRD spectra of CBW. Q = Quartz, C = Calcite, S = Sanidine, A= Albite.

It is worth mentioning that, when clay minerals are heated at a constant rate, there are two main thermal effects, a large endothermic one near 550°C, caused by the dissociation of the clay structure and an intense exothermic peak (between 800-900°C) due to the crystallisation of new crystalline phases such as alumina-silicates (diopside, leucite) [124]. Indeed, the XRD data of the brick visible in Figure n.78, confirmed the presence as main crystalline phase of sodium and potassium aluminium silicates. Quartz mineral (SiO_2) and calcium carbonate ($CaCO_3$) were also detected, as can be seen in Table n.7. The amorphous aluminosilicates formed upon decomposition and destruction of clay minerals during firing cannot be observed by the XRD technique due to their amorphous nature.

Furthermore, from the TGA curve of the sample shown in Figure n.79, a weight loss can be observed at temperatures between 100 °C and 200 °C, due to the evaporation of the free water absorbed in the sample. Subsequently, a small amount of weight loss (≈2%) occurred at temperatures between 650 °C and 750 °C and can be attributed to the decomposition of carbonates present in the raw material or due to atmospheric carbonation that occurred during sample preparation prior to the analysis step. [125]

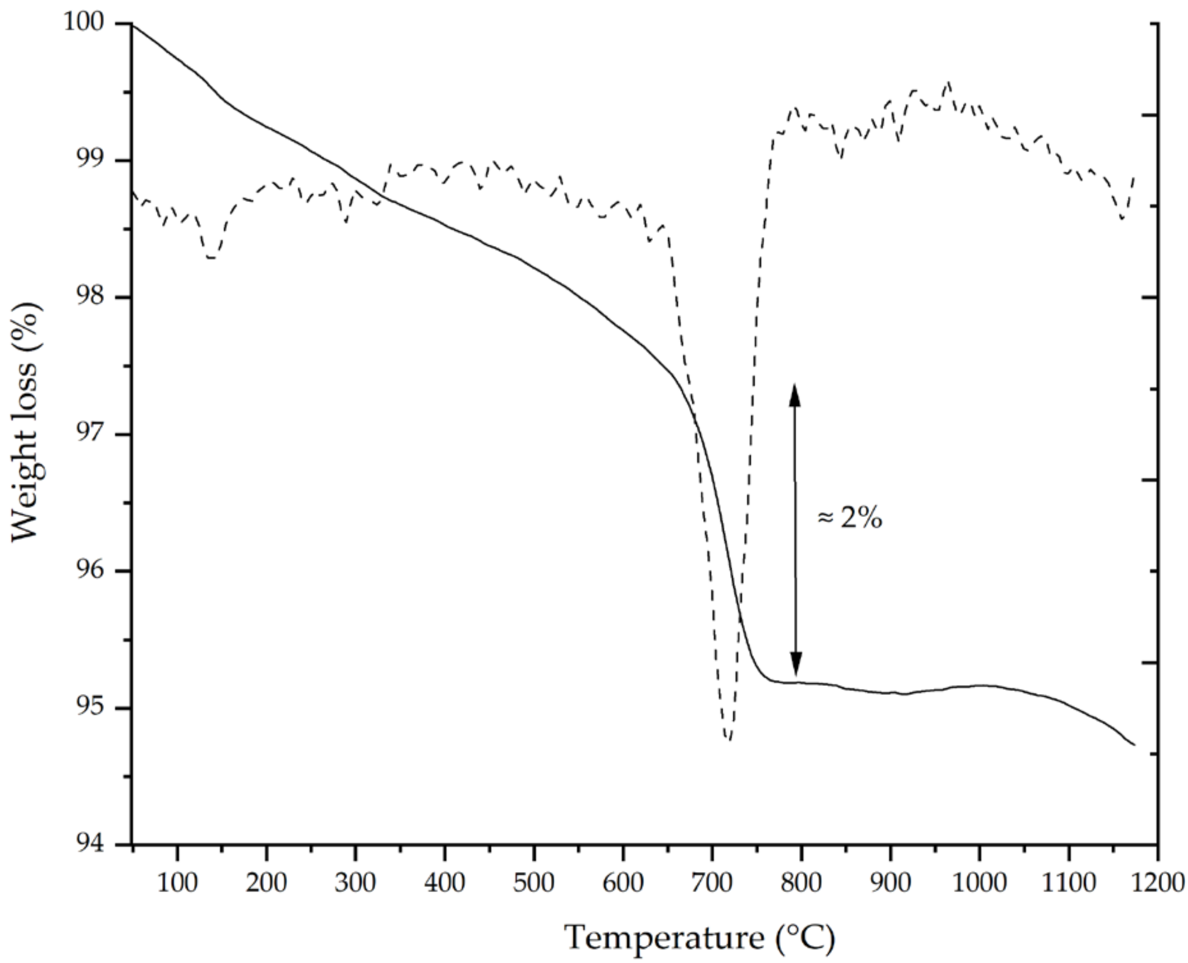


Figure n.79 - TGA curve (solid line) and DTG curve (dashed line) of CBW

5.3. Results of the physical characterisation

The results of the physical characterisation tests, reported in the following paragraphs, relate to the absorption and capillary rise tests carried out in the materials laboratory of the DICMaPI - Department of Chemical Engineering of Materials and Industrial Production of the University of Naples "Federico II".

5.3.1 Results of the capillary rise test

The thirty-one samples made for the capillary absorption test were preliminarily dried and weighed; in table n.8 the weights relative to the single samples for the respective days of observation are reported.

Figure 80 - Capillary rise test

Sample	Initial weight	Weighing 1	Weighing 2	Weighing 3
C 100 1	136,69 g	123,85 g	123,87 g	
C 100 2	137,04 g	123,75 g	123,77 g	
C 100 1 (CUBE)	204,64 g	183,59 g	183,66 g	183,48 g
C 100 2 (CUBO)	206,97 g	184,66 g	184,71 g	184,53 g
C 90 A	134,34 g	121,90 g	121,85 g	121,85 g
C 90 B	128,03 g	117,86 g	117,75 g	117,74 g
C 80 A	121,46 g	116,18 g	116,05 g	116,03 g
C 80 B	137,39 g	124,92 g	124,81 g	124,80 g
C 10 A	135,36 g	127,63 g	127,37 g	127,24 g
C 10 B	134,32 g	126,81 g	126,51 g	126,38 g
CP 100 A	145,07 g	126,05 g	126,12 g	
CP 100 B	237,13 g	204,83 g	204,81 g	
CP 100 C (CUBE)	236,15 g	204,42 g	204,37 g	
CP 90 A	130,98 g	120,01 g	119,88 g	119,82 g
CP 90 B	147,36 g	127,09 g	126,91 g	126,82 g
CP 80 A	124,95 g	119,96 g	119,79 g	119,71 g
CP 80 B	124,06 g	107,95 g	107,85 g	107,79 g
CP 10 A (CUBE)	204,62 g	194,34 g	193,76 g	193,54 g
CP 10 B (CUBE)	205,59 g	195,29 g	194,70 g	194,49 g
T 10	123,95 g	118,70 g	118,33 g	118,08 g
T 80 A	111,54 g	103,84 g	103,66 g	103,65 g
T 80 B	114,77 g	103,47 g	103,22 g	103,22 g
M 80 A	103,23 g	115,49 g	115,25 g	115,38 g
M 80 B	134,63 g	117,43 g	117,16 g	117,27 g
M 90 A	132,80 g	116,09 g	115,92 g	115,97 g
M 90 B	139,61 g	117,03 g	116,91 g	116,82 g
M 100 A	116,64 g	105,39 g		
M 100 B	128,09 g	113,63 g		
M 100 A (CUBE)	188,64 g	168,87 g	168,93 g	168,53 g
M 100 B (CUBE)	190,63 g	168,63 g	168,70 g	168,30 g
M 100 C (CUBE)	128,33 g	113, 46 g	113, 43 g	

Table n.14 - Capillary rise test weights

Figure n.81 - Capillary rise test (samples CP and C)

For the determination of water absorption by capillarity, the UNI EN 15801:2010 standard was followed. The samples produced were placed in contact with deionised water and weighed at defined intervals.

Deionised water and weighed at defined time intervals. Cubic and cylindrical specimens of regular shape were used as prescribed. The samples were then first immersed in water for thirty minutes and dried in an oven for seven days at 60°C; they were then weighed and cooled in a desiccator containing anhydrous silicone gel.

The test was carried out in an environment with controlled humidity and temperature; the samples after the initial weighing (m_0) were placed on 5 mm sheets of filter paper previously soaked in deionised water. Before each weighing, all samples were appropriately blotted. The water absorption by capillarity follows the formula (3) which must be satisfied for the test to be considered satisfactory.

$$\frac{(m_i - m_0) - (m_{i-1} - m_0)}{m_i - m_0} \text{ x } 100 \leq 1 \qquad (3)$$

Where:

m_0, m_i and m_{i-1} represent the mass measured in grams of the specimens at the times t_0, t_i and t_f.

To determine the quantity Q_i of water absorbed per unit area the ratio of the difference in masses to the area of the sample was made. The capillary absorption coefficient was also determined as the ratio between the difference in the quantity of water absorbed after thirty minutes from the start of the test and the intercept relative to the linear line of the absorption graph, and the square root of the time at thirty minutes.

Below are some tables relating to the capillary absorption of the various mixtures.

Cement 10%

	m_{t0}(g)	h(cm)	d(cm)	r(cm)	Q_0 (mg/cm^2)	A (cm^2)
C 10 A	127,01	4,83	4,63	2,315	**-20,979**	16,83
C 10 B	126,28	4,88	4,63	2,315	**-34,977**	16,83

Table n.15 - Starting data (samples C 10 A and B)

SAMPLE			C 10 A				
CA (mg/cm2 √s)			**7,4**				
t (√s)	**t(min)**	**m(g)**	**m-m0**	**Mn-Mn-1**	**%**	**Qi(mg/cm^2)**	
0,00	0,00	127,01	0,000	0,00	0,000%	0,000	
10,95	2,00	128,010	1,000	1,00	0,787%	59,425	
17,32	5,00	128,820	1,810	0,81	1,425%	107,559	
24,49	10,00	129,700	2,690	0,88	2,118%	159,853	
34,64	20,00	130,890	3,880	1,19	3,055%	230,569	
42,43	30,00	131,950	4,940	1,06	3,889%	293,559	
60,00	60,00	134,300	7,290	2,35	5,740%	433,207	
84,85	120,00	137,350	10,340	3,05	8,141%	614,453	
103,92	180,00	140,350	13,340	3,00	10,503%	792,728	
120,00	240,00	141,970	14,960	1,62	11,779%	888,996	
134,16	300,00	143,880	16,870	1,91	13,282%	1002,498	
293,94	1440,00	156,340	29,330	14,37	23,093%	1742,932	
415,69	2880,00	157,000	29,990	13,12	23,612%	1782,152	2,201
509,12	4320,00	157,05	30,04	0,71	0,23651681	1785,12359	0,166

Table n.16 - Sample data C 10 A

SAMPLE				C 10 B			
CA (mg/cm2 √s)				**7,3**			
t (√s)	**t(min)**	**m(g)**	**m-m0**	**Mn-Mn-1**	**%**	**Qi(mg/cm^2)**	
0,00	0,00	126,28	0,000	0,00	0,000%	0,000	
10,95	2,00	127,120	0,840	0,84	0,665%	49,917	
17,32	5,00	127,790	1,510	0,67	1,196%	89,732	
24,49	10,00	128,640	2,360	0,85	1,869%	140,243	
34,64	20,00	130,100	3,820	1,46	3,025%	227,003	
42,43	30,00	130,930	4,650	0,83	3,682%	276,326	
60,00	60,00	133,120	6,840	2,19	5,417%	406,466	
84,85	120,00	136,120	9,840	3,00	7,792%	584,741	
103,92	180,00	139,630	13,350	3,51	10,572%	793,322	
120,00	240,00	140,530	14,250	0,90	11,284%	846,805	
134,16	300,00	141,940	15,660	1,41	12,401%	930,594	
293,94	1440,00	155,190	28,910	14,66	22,894%	1717,973	
415,69	2880,00	155,740	29,460	13,80	23,329%	1750,657	1,867
509,12	4320,00	156,030	29,750		23,559%	1767,890	0,975

Table n.17 - Sample data C 10 B

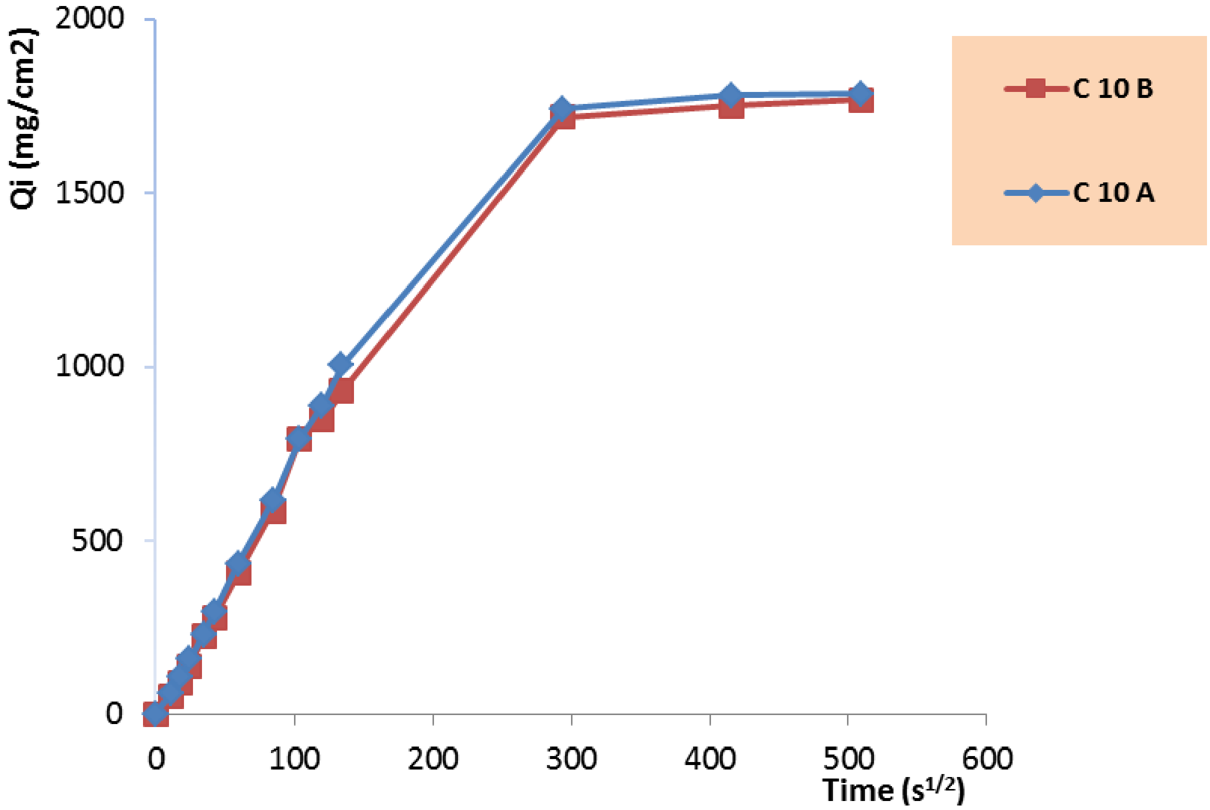


Figure n.82 - Experimental results as the amount of water absorbed (Q) per unit area as a function of time (b) of samples C 10

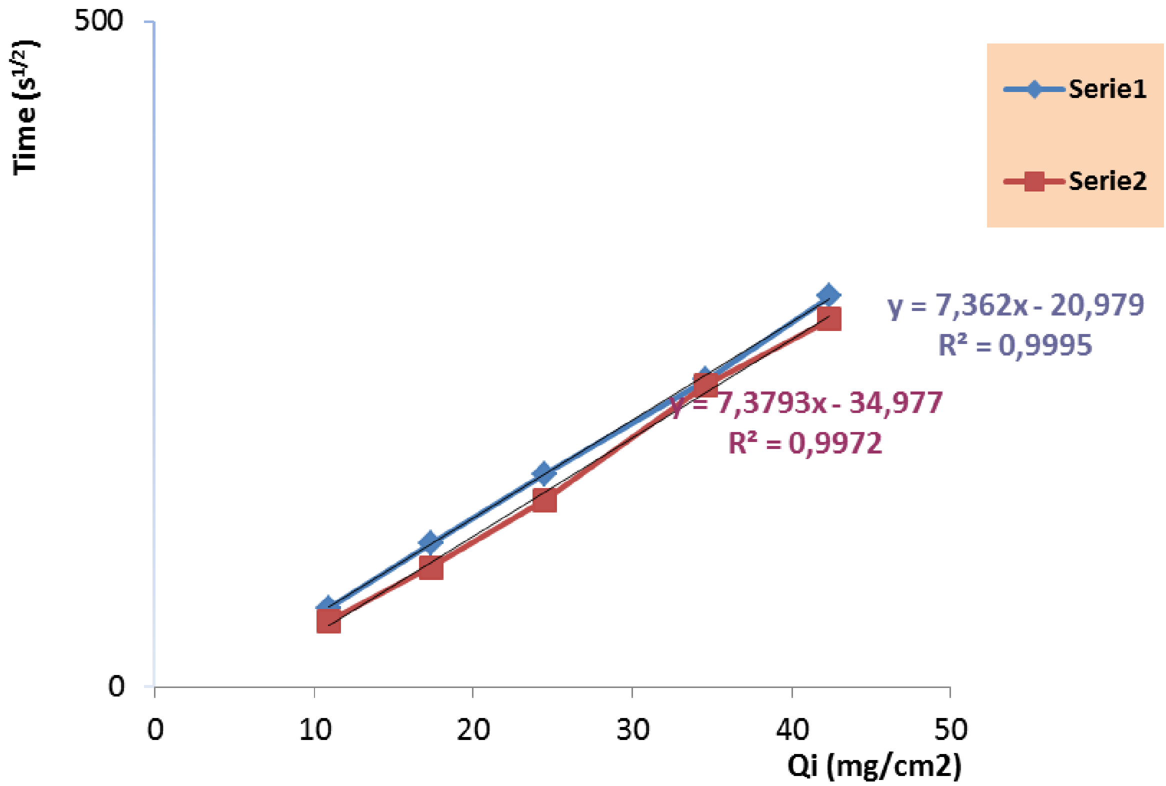


Figure n.83 - Graph showing Q0 value for samples C 10

Cement 80%

	m_{t0}(g)	h(cm)	D(cm)	r(cm)	Q_0 (mg/cm^2)	A (cm^2)
C 80 A	116,03	4,34	4,61	2,305	6,5147	16,68
C 80 B	124,8	4,93	4,58	2,29	-33,272	16,47

Table n.18 - Starting data (samples C 80 A and B)

SAMPLE			C 80 A			
CA (mg/cm2 √s)			**19,1**			
t (√s)	**t(min)**	**m(g)**	**m-m0**	**Mn-Mn-1**	**%**	**Qi(mg/cm^2)**
0,00	0,00	116,03	0,000	0,00	0,000%	0,000
10,95	2,00	119,580	3,550	3,55	3,060%	212,793
17,32	5,00	121,700	5,670	2,12	4,887%	339,869
24,49	10,00	124,060	8,030	2,36	6,921%	481,331
34,64	20,00	127,200	11,170	3,14	9,627%	669,548
42,43	30,00	129,680	13,650	2,48	11,764%	818,203
60,00	60,00	134,230	18,200	4,55	15,686%	1090,938
84,85	120,00	135,450	19,420	1,22	16,737%	1164,066
103,92	180,00	135,960	19,930	0,51	17,177%	1194,637
120,00	240,00	136,200	20,170	0,24	17,383%	1209,023
134,16	300,00	136,370	20,340	0,17	17,530%	1219,213
293,94	1440,00	138,470	22,440	2,10	19,340%	1345,090

Table n.19 - Sample data C 80 A

SAMPLE				C 80 B		
CA (mg/cm2 √s)			**16,6**			
t (√s)	**t(min)**	**m(g)**	**m-m0**	**Mn-Mn-1**	**%**	**Qi(mg/cm^2)**
0,00	0,00	124,8	0,000	0,00	0,000%	0,000
10,95	2,00	127,420	2,620	2,62	2,099%	159,111
17,32	5,00	128,820	4,020	1,40	3,221%	244,132
24,49	10,00	130,650	5,850	1,83	4,688%	355,267
34,64	20,00	133,490	8,690	2,84	6,963%	527,739
42,43	30,00	135,860	11,060	2,37	8,862%	671,668
60,00	60,00	141,490	16,690	5,63	13,373%	1013,575
84,85	120,00	148,320	23,520	6,83	18,846%	1428,357
103,92	180,00	149,320	24,520	1,00	19,647%	1489,086
120,00	240,00	149,770	24,970	0,45	20,008%	1516,415
134,16	300,00	150,070	25,270	0,30	20,248%	1534,633
293,94	1440,00	152,040	27,240	1,97	21,827%	1654,270

Table n.20 - Sample data C 80 B

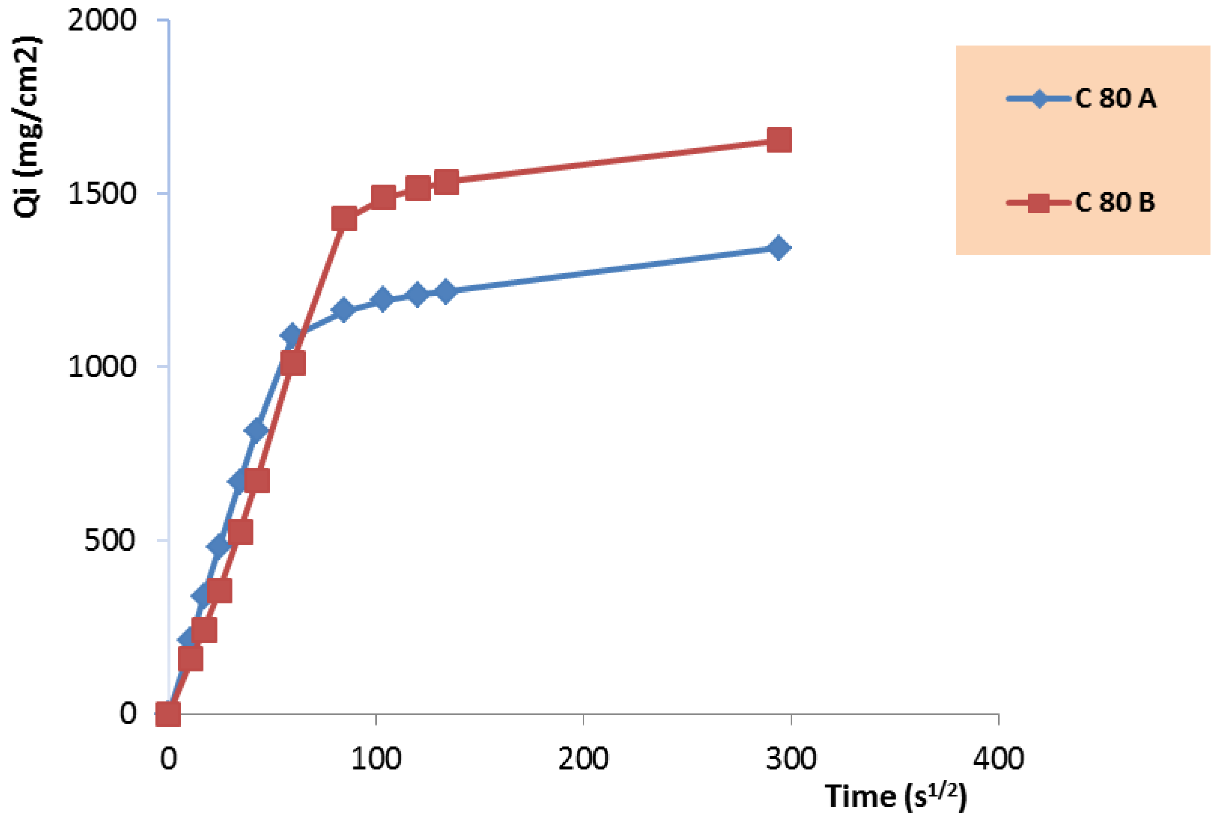


Figure n.84 - Experimental results as quantity of water absorbed (Q) per unit area as a function of time (b) of samples C 80

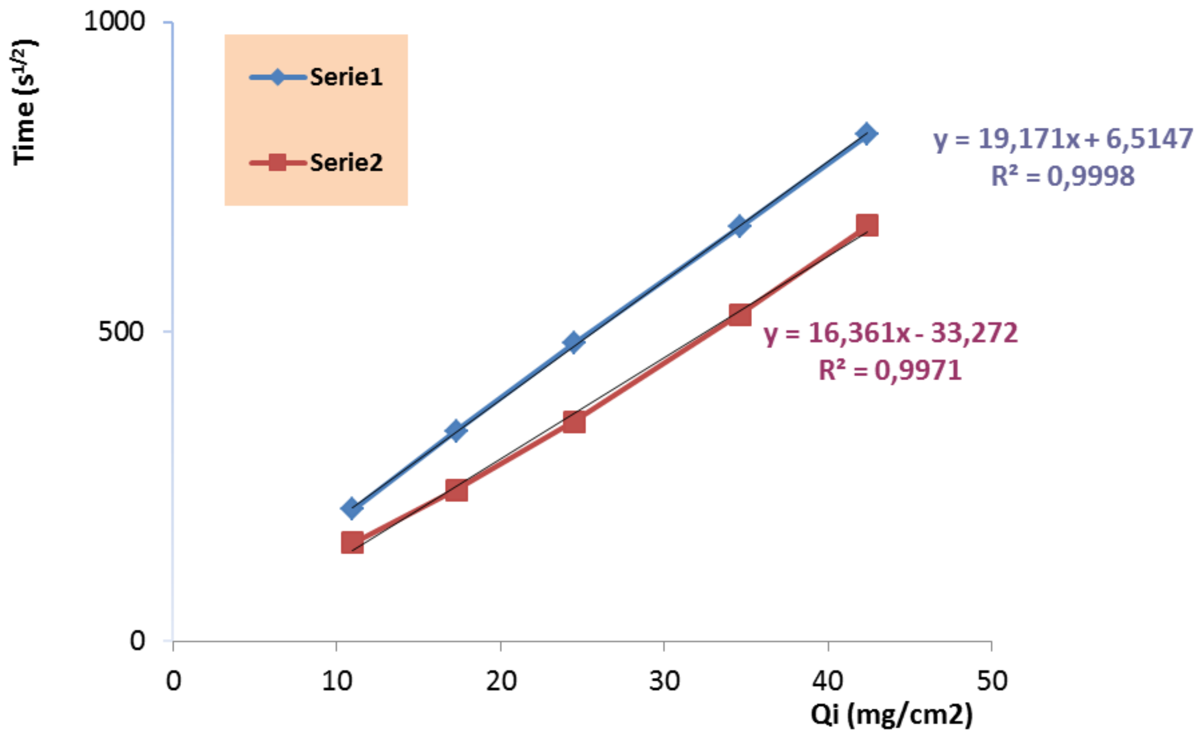


Figure n.85 - Graph showing the Q0 value for samples C 80

Cement 90%

	m_{t0}(g)	h(cm)	d(cm)	r(cm)	Q_0 (mg/cm^2)	A (cm^2)
C 90 A	121,85	4,92	4,64	2,32	49,901	16,90
C 90 B	117,74	4,45	4,64	2,32	26,079	16,90

Table n.21 - Starting data (samples C 90 A and B)

SAMPLE			C 90 A			
CA (mg/cm2 √s)			**21,1**			
t (√s)	**t(min)**	**m(g)**	**m-m0**	**Mn-Mn-1**	**%**	**Qi(mg/cm^2)**
0,00	0,00	121,85	0,000	0,00	0,000%	0,000
10,95	2,00	126,560	4,710	4,71	3,865%	278,686
17,32	5,00	128,900	7,050	2,34	5,786%	417,142
24,49	10,00	131,660	9,810	2,76	8,051%	580,448
34,64	20,00	135,420	13,570	3,76	11,137%	802,924
42,43	30,00	137,800	15,950	2,38	13,090%	943,746
60,00	60,00	141,470	19,620	3,67	16,102%	1160,896
84,85	120,00	143,020	21,170	1,55	17,374%	1252,608
103,92	180,00	143,810	21,960	0,79	18,022%	1299,352
120,00	240,00	144,620	22,770	0,81	18,687%	1347,279
134,16	300,00	145,200	23,350	0,58	19,163%	1381,597
293,94	1440,00	149,520	27,670	4,32	22,708%	1637,207

Table n.22 - Sample data C 90 A

SAMPLE				C 90 B		
CA (mg/cm2 √s)				**17,6**		
t (√s)	**t(min)**	**m(g)**	**m-m0**	**Mn-Mn-1**	**%**	**Qi(mg/cm^2)**
0,00	0,00	117,74	0,000	0,00	0,000%	0,000
10,95	2,00	121,430	3,690	3,69	3,134%	218,334
17,32	5,00	123,360	5,620	1,93	4,773%	332,530
24,49	10,00	125,510	7,770	2,15	6,599%	459,743
34,64	20,00	128,520	10,780	3,01	9,156%	637,842
42,43	30,00	130,830	13,090	2,31	11,118%	774,522
60,00	60,00	135,640	17,900	4,81	15,203%	1059,125
84,85	120,00	137,330	19,590	1,69	16,638%	1159,121
103,92	180,00	138,160	20,420	0,83	17,343%	1208,231
120,00	240,00	138,720	20,980	0,56	17,819%	1241,366
134,16	300,00	139,010	21,270	0,29	18,065%	1258,525
293,94	1440,00	141,110	23,370	2,10	19,849%	1382,780

Table n.23 - Sample data C 90 B

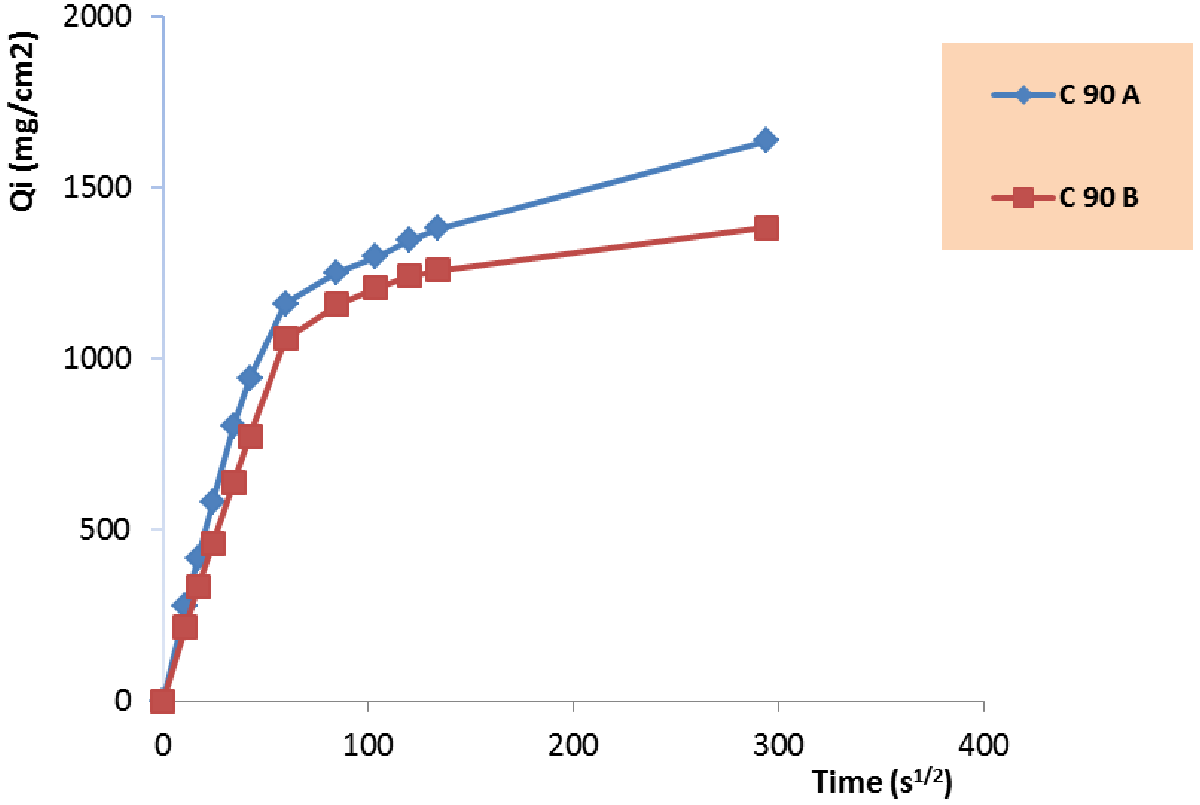


Figure n.86 - Experimental results as quantity of water absorbed (Q) per unit area as a function of time (b) of samples C 90

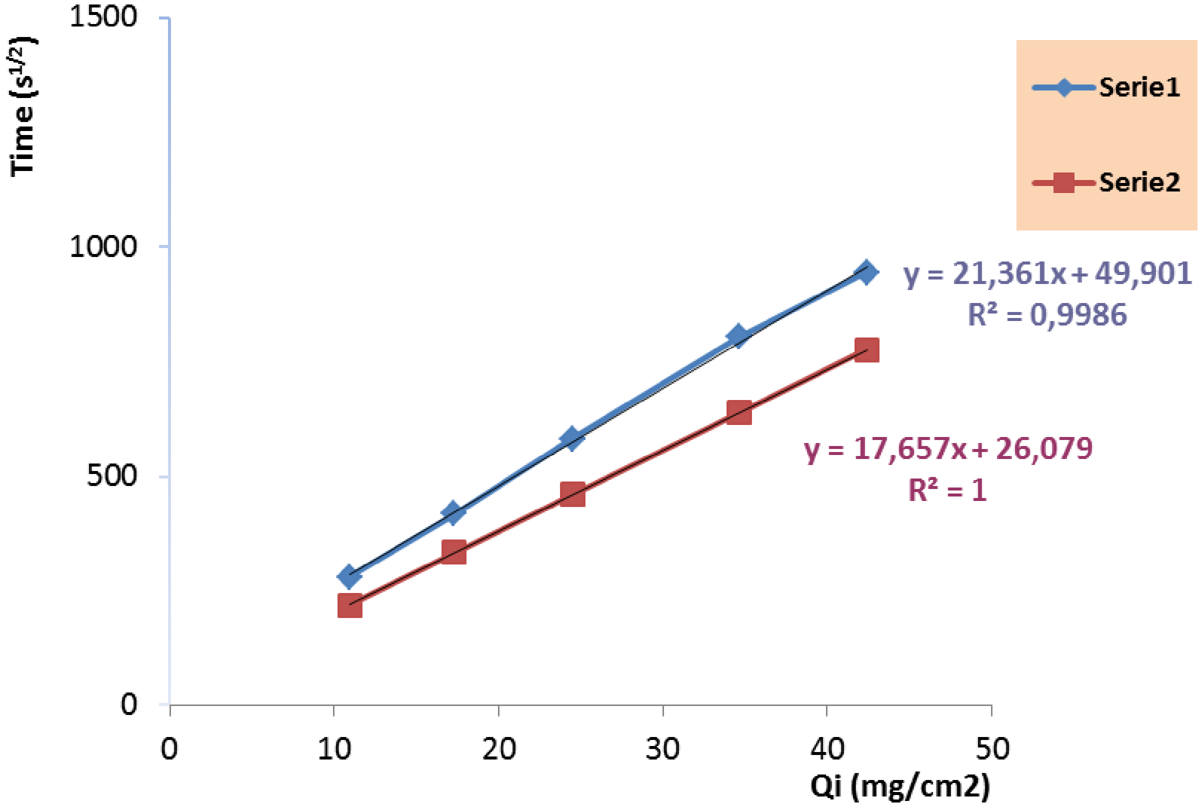


Figure n.87 - Graph of the Q0 value for samples C 90

Cement 100%

	m_{t0}(g)	h(cm)	d(cm)	r(cm)	Q_0 (mg/cm^2)	A (cm^2)
CDW100 1	123,87	4,88	4,55	2,28	2,3196	16,25
CDW100 2	123,77	4,89	4,56	2,28	126,15	16,32

Table n.24 - Starting data (samples C 100 A and B)

PROVINO			C 100 A			
CA (mg/cm2 √s)			**15,9**			
t (√s)	**t(min)**	**m(g)**	**m-m0**	**Mn-Mn-1**	**%**	**Qi(mg/cm^2)**
0,00	0,00	123,87	0,000	0,00	0,000%	0,000
10,95	2,00	126,760	2,890	2,89	2,333%	177,830
17,32	5,00	128,410	4,540	1,65	3,665%	279,359
24,49	10,00	130,050	6,180	1,64	4,989%	380,273
34,64	20,00	132,780	8,910	2,73	7,193%	548,258
42,43	30,00	134,860	10,990	2,08	8,872%	676,247
60,00	60,00	139,740	15,870	4,88	12,812%	976,527
84,85	120,00	145,220	21,350	5,48	17,236%	1313,728
103,92	180,00	148,310	24,440	3,09	19,730%	1503,865
120,00	240,00	151,790	27,920	3,48	22,540%	1717,999
134,16	300,00	153,890	30,020	2,10	24,235%	1847,218
293,94	1440,00	155,83	31,96	1,94	0,26	1966,59
415,69	2880,00	155,80	31,93	-0,03	0,26	1964,75
509,12	4320,00	155,68	31,81	-0,12	0,26	1957,36

Table n.25 - Sample data C 100 A

PROVINO				C 100 B		
CA (mg/cm2 √s)				**15,1**		
t (√s)	**t(min)**	**m(g)**	**m-m0**	**Mn-Mn-1**	**%**	**Qi(mg/cm^2)**
0,00	0,00	123,77	0,000	0,00	0,000%	0,000
10,95	2,00	128,570	4,800	4,80	3,878%	294,064
17,32	5,00	130,080	6,310	1,51	5,098%	386,572
24,49	10,00	131,530	7,760	1,45	6,270%	475,404
34,64	20,00	133,950	10,180	2,42	8,225%	623,661
42,43	30,00	136,280	12,510	2,33	10,107%	766,404
60,00	60,00	141,380	17,610	5,10	14,228%	1078,847
84,85	120,00	146,600	22,830	5,22	18,446%	1398,642
103,92	180,00	148,960	25,190	2,36	20,352%	1543,223
120,00	240,00	151,200	27,430	2,24	22,162%	1680,453
134,16	300,00	153,470	29,700	2,27	23,996%	1819,521
293,94	1440,00	155,300	31,530	1,83	25,475%	1931,633
415,69	2880,00	155,15	31,38	-0,15	0,25	1922,444
509,12	4320,00	155,00	31,23	-0,15	0,25	1913,254

Table n.26 - Sample data C 100 B

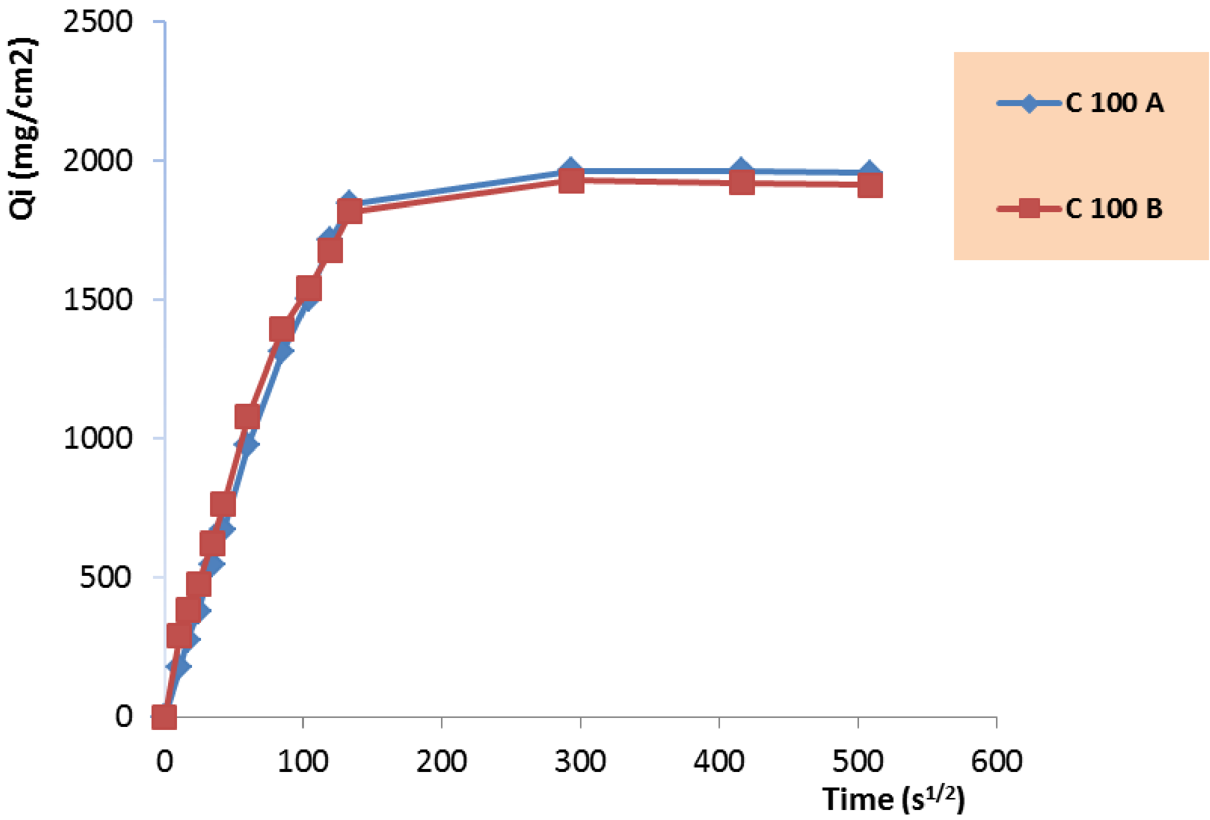


Figure n.88 - Experimental results as the amount of water absorbed (Q) per unit area as a function of time (b) of samples C 100

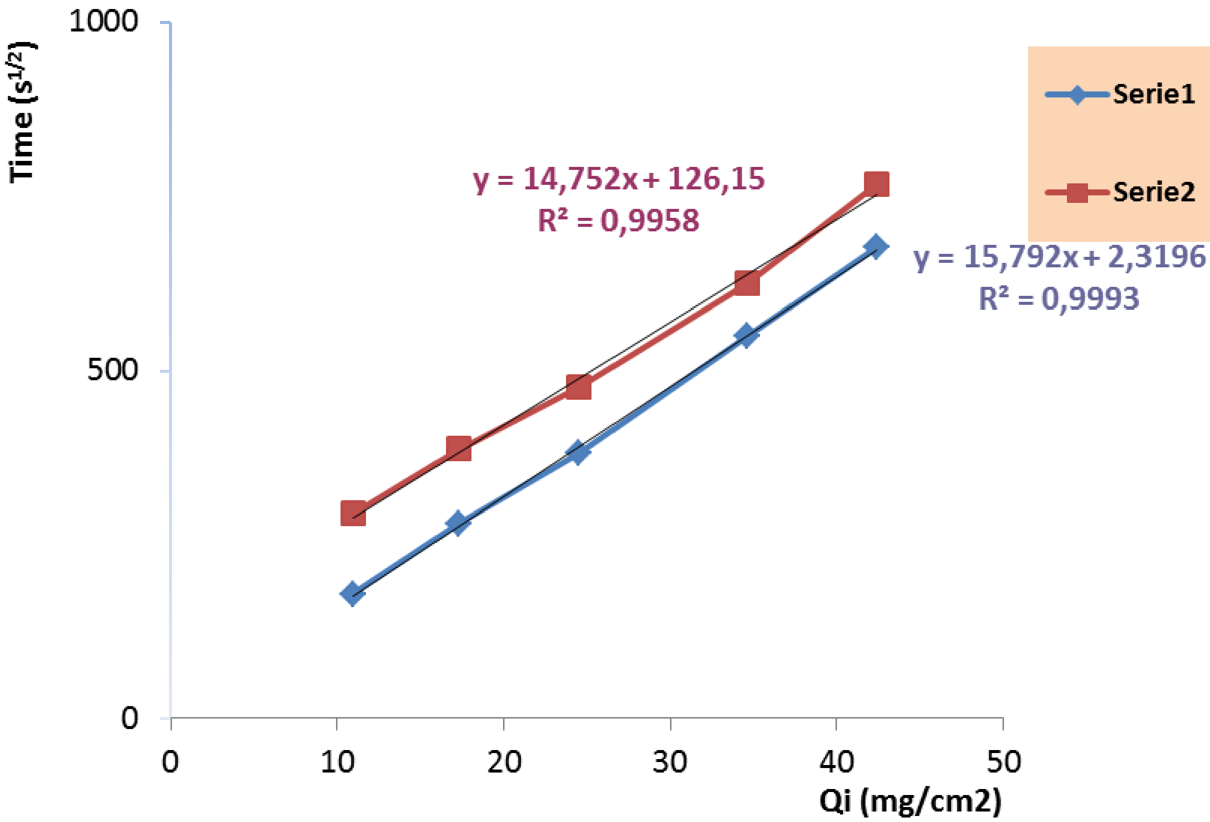


Figure n.89 - Graph of the Q0 value for samples C 100

Cocciopesto 80%

	m_{t0}(g)	h(cm)	d(cm)	r(cm)	Q_0 (mg/cm2)	A (cm2)
CP80 A	119,52	4,26	4,63	2,315	**-45,449**	16,83
CP80 B	107,69	4,43	4,57	2,285	**16,82**	16,39

Table n.27 - Starting data (samples CP 80 A and B)

SAMPLE			**CP80 A**			
CA (mg/cm2 √s)			**18,7**			
t (√s)	**t(min)**	**m(g)**	**m-m0**	**Mn-Mn-1**	**%**	**Qi(mg/cm^2)**
0,00	0,00	119,52	0,000	0,00	0,000%	0,000
10,95	2,00	122,110	2,590	2,59	2,167%	153,910
17,32	5,00	124,320	4,800	2,21	4,016%	285,239
24,49	10,00	126,500	6,980	2,18	5,840%	414,786
34,64	20,00	129,630	10,110	3,13	8,459%	600,786
42,43	30,00	132,110	12,590	2,48	10,534%	748,159
60,00	60,00	134,790	15,270	2,68	12,776%	907,418
84,85	120,00	135,940	16,420	1,15	13,738%	975,757
103,92	180,00	136,460	16,940	0,52	14,173%	1006,658
120,00	240,00	136,660	17,140	0,20	14,341%	1018,543
134,16	300,00	136,930	17,410	0,27	14,567%	1034,587
293,94	1440,00	138,460	18,940	1,53	15,847%	1125,507
415,69	2880,00	139,260	19,740	0,80	16,516%	1173,047
509,12	4320,00	139,530	20,010	0,27	0,16741968	1189,09198
587,88	5760,00	139,710	20,190	0,18	16,893%	1199,788

Table n.28 - Sample data CP 80 A

SAMPLE				**CP80 B**		
CA (mg/cm2 √s)			**20,3**			
t (√s)	**t(min)**	**m(g)**	**m-m0**	**Mn-Mn-1**	**%**	**Qi(mg/cm^2)**
0,00	0,00	107,69	0,000	0,00	0,000%	0,000
10,95	2,00	111,330	3,640	3,64	3,380%	222,024
17,32	5,00	114,040	6,350	2,71	5,897%	387,322
24,49	10,00	117,190	9,500	3,15	8,822%	579,457
34,64	20,00	120,890	13,200	3,70	12,257%	805,141
42,43	30,00	122,120	14,430	1,23	13,400%	880,165
60,00	60,00	122,980	15,290	0,86	14,198%	932,622
84,85	120,00	123,480	15,790	0,50	14,662%	963,119
103,92	180,00	123,810	16,120	0,33	14,969%	983,248
120,00	240,00	123,960	16,270	0,15	15,108%	992,397
134,16	300,00	124,160	16,470	0,20	15,294%	1004,596
293,94	1440,00	125,380	17,690	1,22	16,427%	1079,011
415,69	2880,00	125,850	18,160	0,47	16,863%	1107,679
509,12	4320,00	126,150	18,460	0,30	0,17141796	1125,97731
587,88	5760,00	126,340	18,650	0,19	17,318%	1137,566

Table n.29 - Data relating to sample CP 80 B

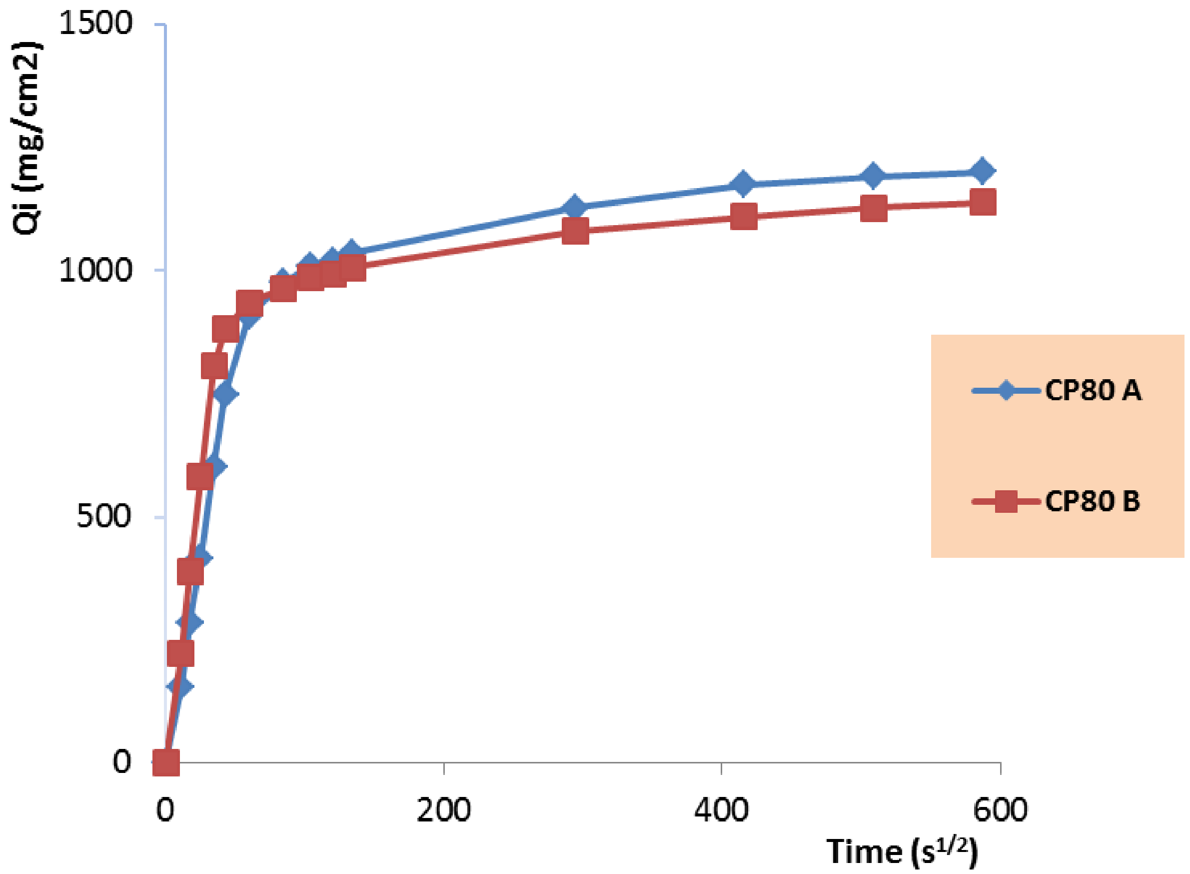


Figure n.90 - Experimental results as the amount of water absorbed (Q) per unit area as a function of time (b) of samples CP 80

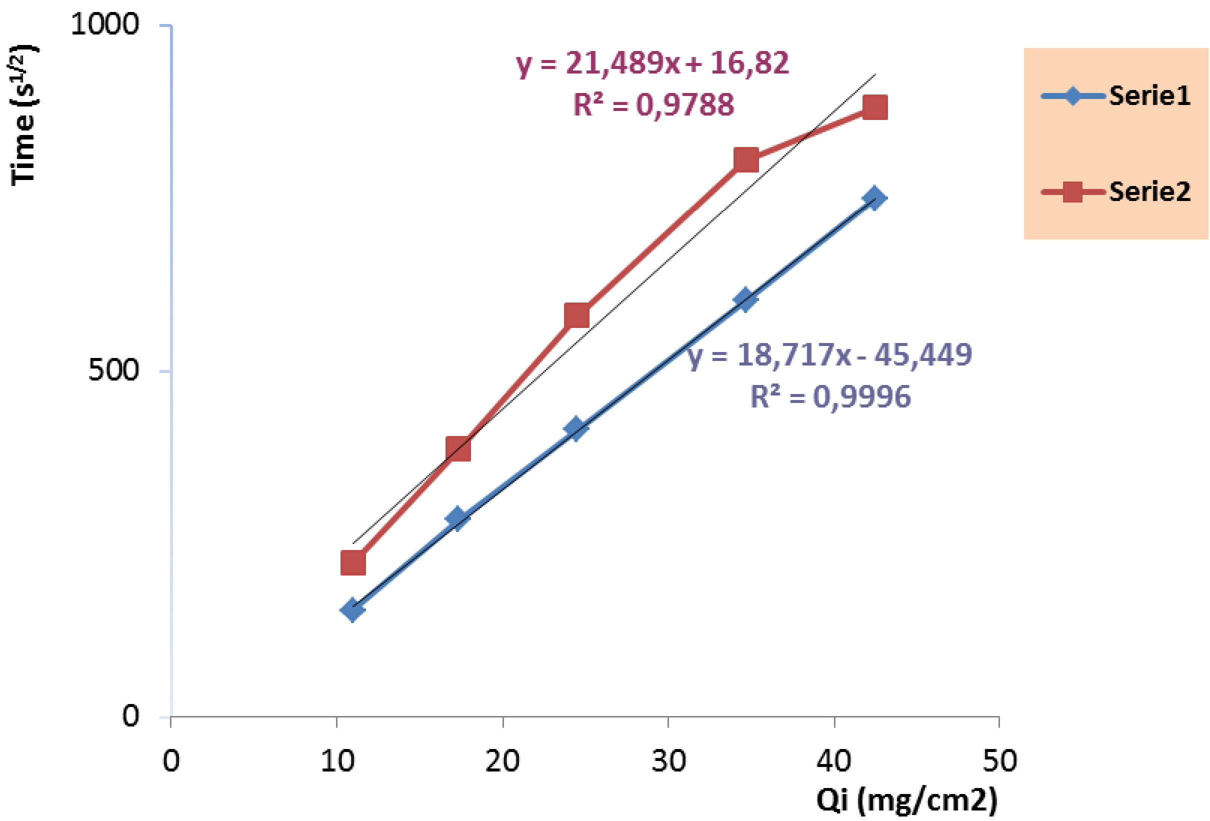


Figure n.91 - Graph showing the Q0 value for samples CP 80

Cocciopesto 90%

	m_{t0}(g)	h(cm)	d(cm)	r(cm)	Q_0 (mg/cm^2)	A (cm^2)
CP90 A	119,67	4,26	4,63	2,315	**-27,155**	16,83
CP90 B	126,67	4,43	4,57	2,285	**80,9**	16,39

Table n.30 - Starting data (samples CP 90 A and B)

SAMPLE			CP90 A			
CA (mg/cm2 √s)			**21,6**			
t (√s)	**t(min)**	**m(g)**	**m-m0**	**Mn-Mn-1**	**%**	**Qi(mg/cm^2)**
0,00	0,00	119,67	0,000	0,00	0,000%	0,000
10,95	2,00	123,060	3,390	3,39	2,833%	201,450
17,32	5,00	125,830	6,160	2,77	5,147%	366,057
24,49	10,00	128,770	9,100	2,94	7,604%	540,766
34,64	20,00	133,300	13,630	4,53	11,390%	809,961
42,43	30,00	134,670	15,000	1,37	12,534%	891,373
60,00	60,00	135,170	15,500	0,50	12,952%	921,086
84,85	120,00	135,590	15,920	0,42	13,303%	946,044
103,92	180,00	135,890	16,220	0,30	13,554%	963,872
120,00	240,00	136,080	16,410	0,19	13,713%	975,162
134,16	300,00	136,290	16,620	0,21	13,888%	987,642
293,94	1440,00	137,450	17,780	1,16	14,858%	1056,574

Table n.31 - CP 90 A sample data

SAMPLE				CP90 B		
CA (mg/cm2 √s)				**22,1**		
t (√s)	**t(min)**	**m(g)**	**m-m0**	**Mn-Mn-1**	**%**	**Qi(mg/cm^2)**
0,00	0,00	126,67	0,000	0,00	0,000%	0,000
10,95	2,00	130,770	4,100	4,10	3,237%	250,082
17,32	5,00	135,430	8,760	4,66	6,916%	534,321
24,49	10,00	139,390	12,720	3,96	10,042%	775,863
34,64	20,00	142,700	16,030	3,31	12,655%	977,758
42,43	30,00	143,390	16,720	0,69	13,200%	1019,845
60,00	60,00	144,000	17,330	0,61	13,681%	1057,052
84,85	120,00	144,510	17,840	0,51	14,084%	1088,160
103,92	180,00	144,890	18,220	0,38	14,384%	1111,338
120,00	240,00	145,180	18,510	0,29	14,613%	1129,027
134,16	300,00	145,360	18,690	0,18	14,755%	1140,006
293,94	1440,00	146,940	20,270	1,58	16,002%	1236,379

Table n.32 - Data relating to sample CP 90 B

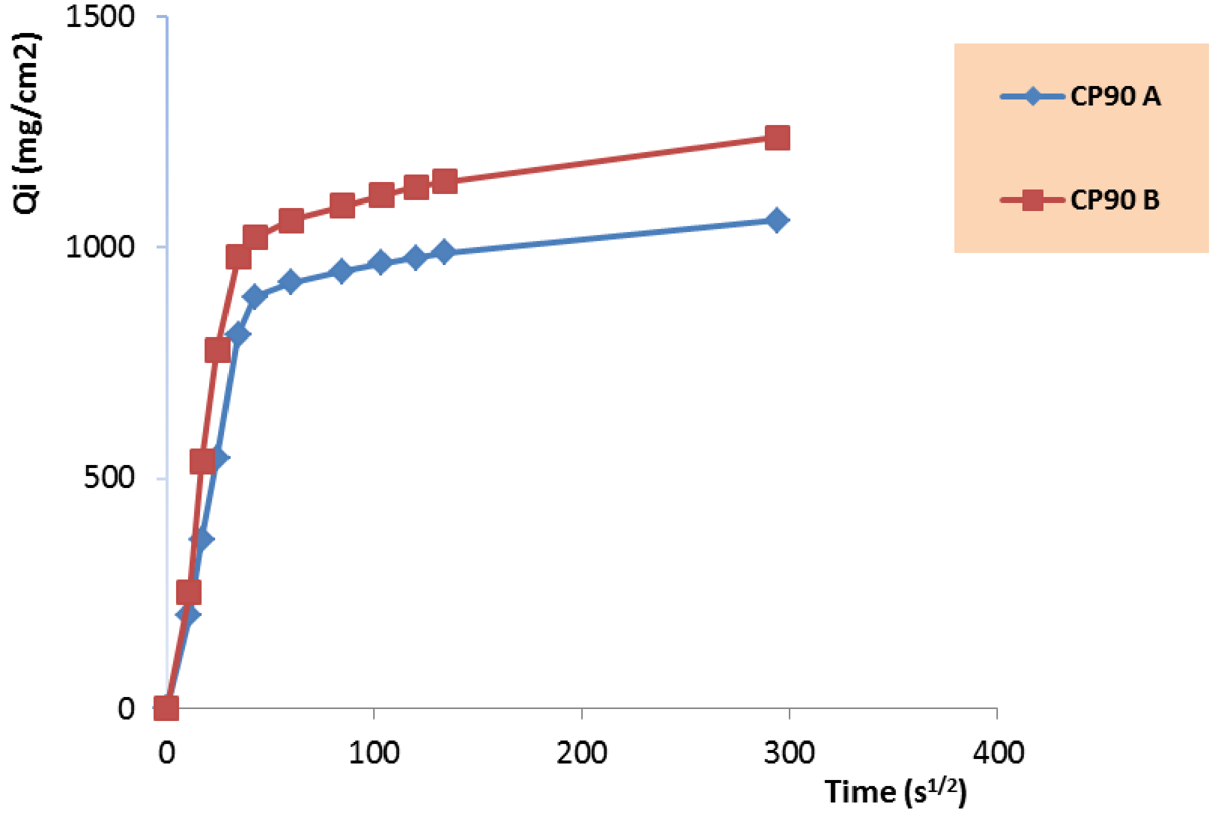


Figure n.92 - Experimental results as the amount of water absorbed (Q) per unit area as a function of time (b) of samples CP 90

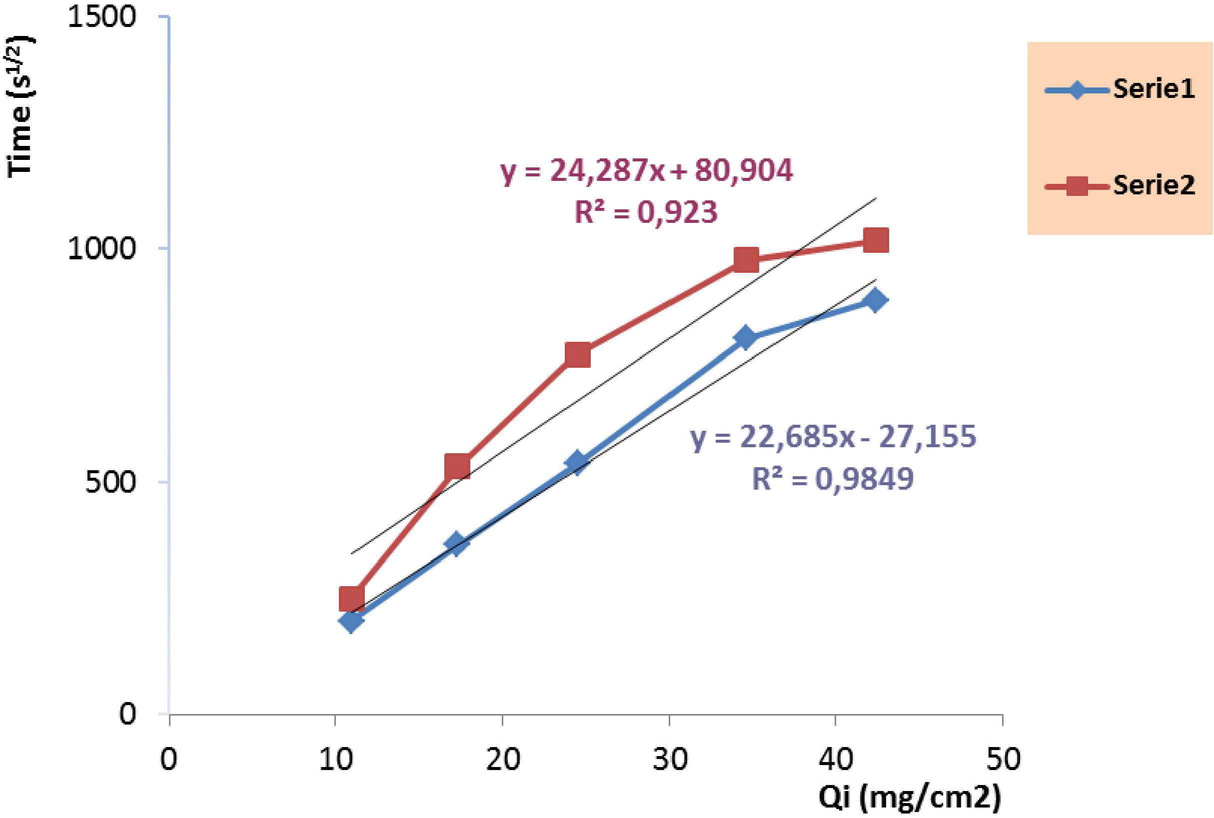


Figure n.93 - Graph of the Q0 value for samples CP 90

Cocciopesto 100%

	m_{t0}(g)	h(cm)	d(cm)	r(cm)	Q_0 (mg/cm^2)	A (cm^2)
CP100 A	126,12	4,54	4,57	2,285	-187,36	16,39
CP100 B	207,77	5,3	4,72	2,36	426,12	25,02

Table n.33 - Starting data (samples CP 100 A and B)

SAMPLE			CP100 A			
CA (mg/cm2 √s)			29,7			
t (√s)	t(min)	m(g)	m-m0	Mn-Mn-1	%	Qi(mg/cm^2)
0,00	0,00	126,12	0,000	0,00	0,000%	0,000
10,95	2,00	127,540	1,420	1,42	1,126%	86,614
17,32	5,00	130,670	4,550	3,13	3,608%	277,530
24,49	10,00	141,230	15,110	10,56	11,981%	921,642
34,64	20,00	143,370	17,250	2,14	13,677%	1052,173
42,43	30,00	143,690	17,570	0,32	13,931%	1071,691
60,00	60,00	144,110	17,990	0,42	14,264%	1097,309
84,85	120,00	144,600	18,480	0,49	14,653%	1127,197
103,92	180,00	144,910	18,790	0,31	14,899%	1146,106
120,00	240,00	145,190	19,070	0,28	15,121%	1163,185
134,16	300,00	145,400	19,280	0,21	15,287%	1175,994
293,94	1440,00	146,920	20,800	1,52	16,492%	1268,707
415,69	2880,00	147,630	21,510	0,71	17,055%	1312,014
509,12	4320,00	147,990	21,870	0,36	0,17340628	1333,97204
587,88	5760,00	148,250	22,130	0,26	17,547%	1349,831

Table n.34 - Data relating to sample CP 100 A

SAMPLE				CP100 B		
CA (mg/cm2 √s)				14,8		
t (√s)	t(min)	m(g)	m-m0	Mn-Mn-1	%	Qi(mg/cm^2)
0,00	0,00	207,77	0,000	0,00	0,000%	0,000
10,95	2,00	218,860	11,090	11,09	5,338%	443,316
17,32	5,00	228,230	20,460	9,37	9,847%	817,877
24,49	10,00	233,030	25,260	4,80	12,158%	1009,754
34,64	20,00	233,720	25,950	0,69	12,490%	1037,336
42,43	30,00	234,170	26,400	0,45	12,706%	1055,325
60,00	60,00	234,930	27,160	0,76	13,072%	1085,705
84,85	120,00	235,820	28,050	0,89	13,501%	1121,282
103,92	180,00	236,430	28,660	0,61	13,794%	1145,667
120,00	240,00	236,790	29,020	0,36	13,967%	1160,058
134,16	300,00	237,080	29,310	0,29	14,107%	1171,650
293,94	1440,00	239,880	32,110	2,80	15,455%	1283,579
415,69	2880,00	240,810	33,040	0,93	15,902%	1320,755
509,12	4320,00	241,040	33,270	0,23	0,16012899	1329,94883
587,88	5760,00	241,130	33,360	0,09	16,056%	1333,547

Table n.35 - Sample data CP 100 B

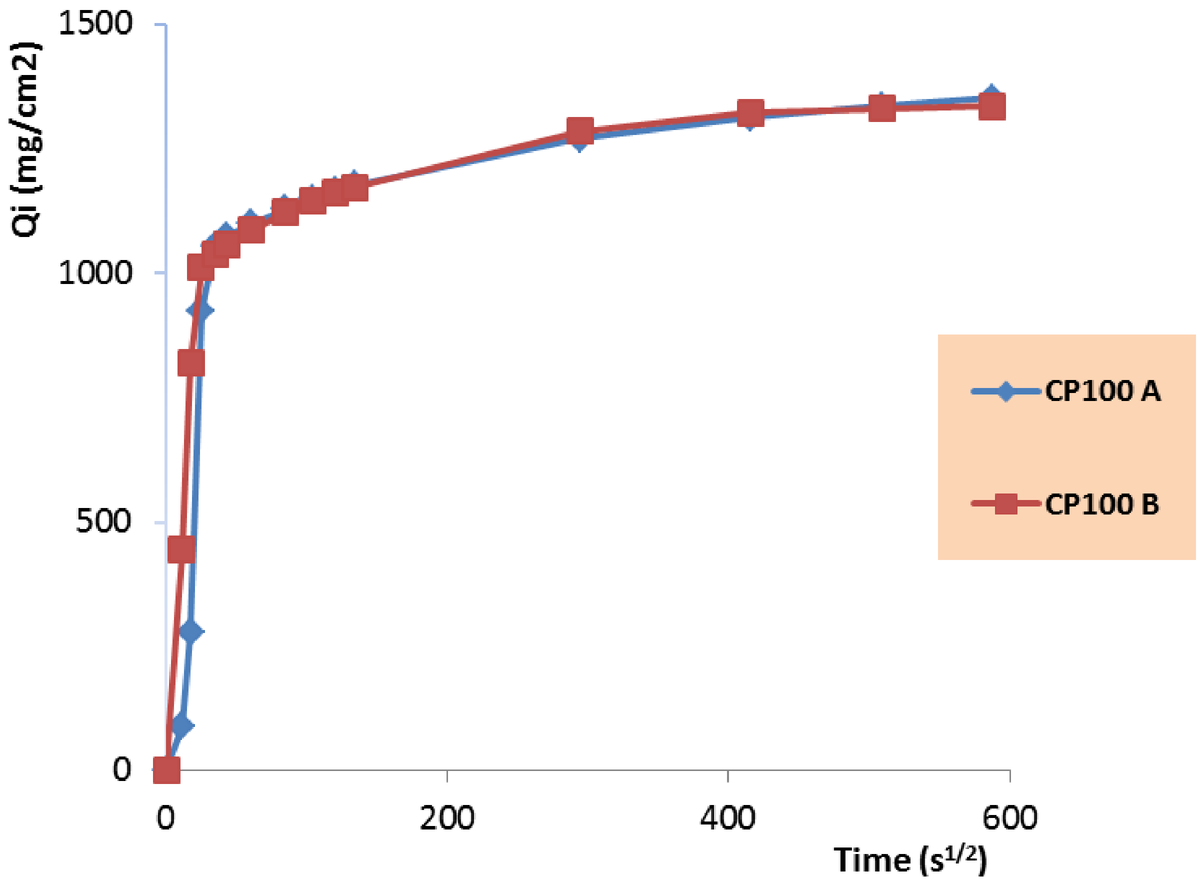


Figure n.94 - Experimental results as the amount of water absorbed (Q) per unit area as a function of time (b) of samples CP 100

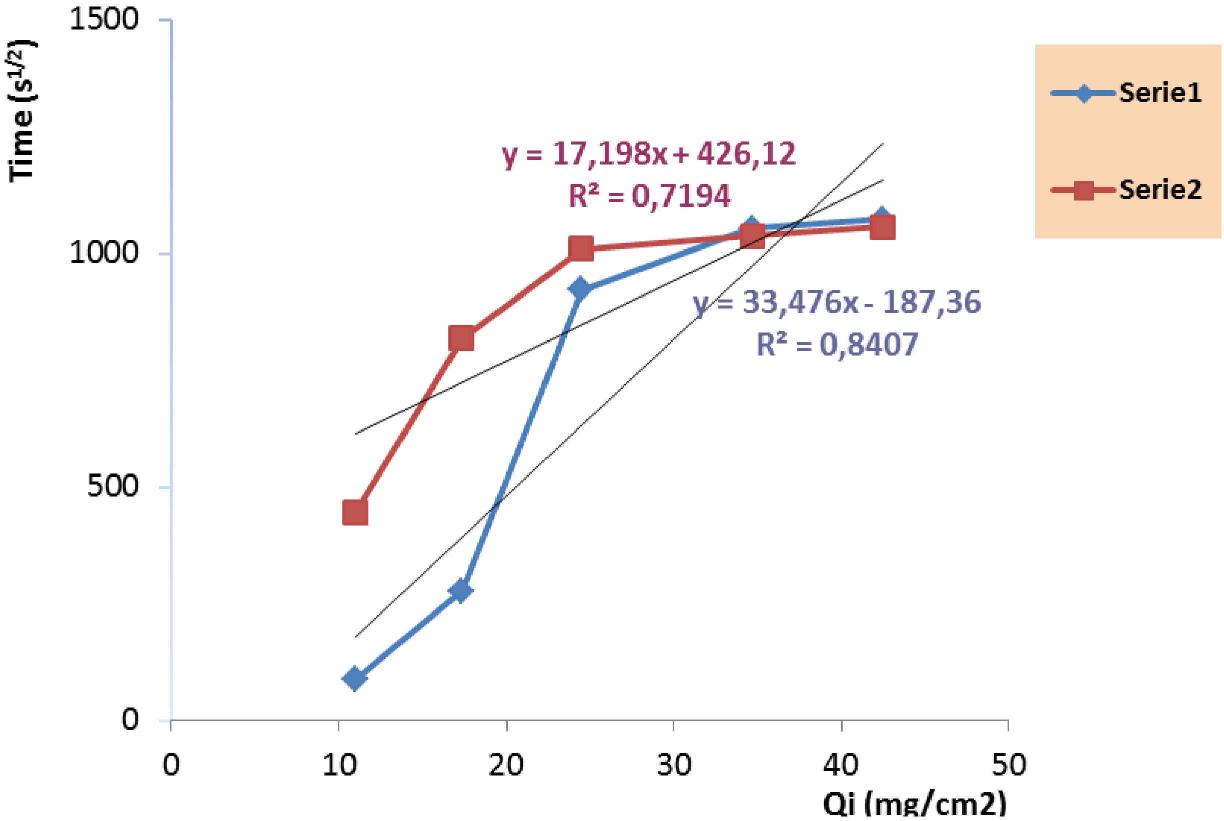


Figure n.95 - Graph of Q0 value for CP 100 samples

Mixed 80%

	m_{t0}(g)	h(cm)	d(cm)	r(cm)	Q_0 (mg/cm^2)	A (cm^2)
M80 A	115,38	4,55	4,52	2,26	-10,174	16,04
M80 B	117,27	4,78	4,55	2,275	91,898	16,25

Table n.36 - Starting data (samples M 80 A and B)

SAMPLE			M80 A			
CA (mg/cm2 √s)			**17,6**			
t (√s)	**t(min)**	**m(g)**	**m-m0**	**Mn-Mn-1**	**%**	**Qi(mg/cm^2)**
0,00	0,00	115,38	0,000	0,00	0,000%	0,000
10,95	2,00	118,340	2,960	2,96	2,565%	184,563
17,32	5,00	120,080	4,700	1,74	4,073%	293,056
24,49	10,00	122,110	6,730	2,03	5,833%	419,632
34,64	20,00	125,070	9,690	2,96	8,398%	604,195
42,43	30,00	127,180	11,800	2,11	10,227%	735,759
60,00	60,00	132,290	16,910	5,11	14,656%	1054,380
84,85	120,00	138,480	23,100	6,19	20,021%	1440,341
103,92	180,00	140,610	25,230	2,13	21,867%	1573,152
120,00	240,00	140,850	25,470	0,24	22,075%	1588,117
134,16	300,00	141,130	25,750	0,28	22,318%	1605,575
293,94	1440,00	143,860	28,480	2,73	24,684%	1775,798
415,69	2880,00	144,630	29,250	0,77	25,351%	1823,809
509,12	4320,00	144,770	29,390	0,14	0,25472352	1832,5383

Table n.37 - Sample data M 80 A

SAMPLE				M80 B		
CA (mg/cm2 √s)				**13,6**		
t (√s)	**t(min)**	**m(g)**	**m-m0**	**Mn-Mn-1**	**%**	**Qi(mg/cm^2)**
0,00	0,00	117,27	0,000	0,00	0,000%	0,000
10,95	2,00	118,950	1,680	1,68	1,433%	103,375
17,32	5,00	120,850	3,580	1,90	3,053%	220,288
24,49	10,00	122,970	5,700	2,12	4,861%	350,738
34,64	20,00	125,870	8,600	2,90	7,334%	529,183
42,43	30,00	128,170	10,900	2,30	9,295%	670,709
60,00	60,00	133,520	16,250	5,35	13,857%	999,910
84,85	120,00	140,870	23,600	7,35	20,124%	1452,177
103,92	180,00	144,840	27,570	3,97	23,510%	1696,463
120,00	240,00	145,110	27,840	0,27	23,740%	1713,077
134,16	300,00	145,450	28,180	0,34	24,030%	1733,998
293,94	1440,00	147,390	30,120	1,94	25,684%	1853,372
415,69	2880,00	147,520	30,250	0,13	25,795%	1861,371
509,12	4320,00	147,590	30,320	0,07	0,25854865	1865,67824

Table n.38 - Sample data M 80 B

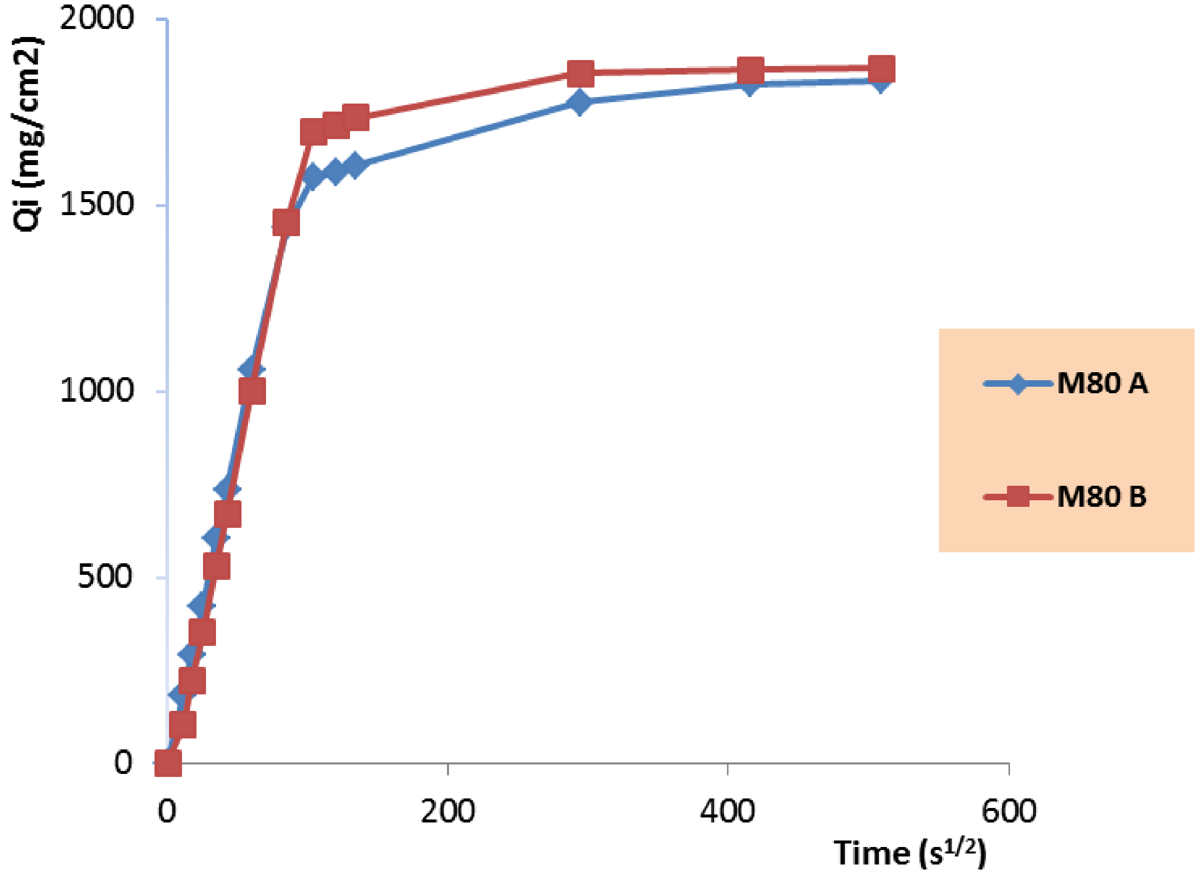


Figure n.96 - Experimental results as quantity of water absorbed (Q) per unit area as a function of time (b) of samples M 80

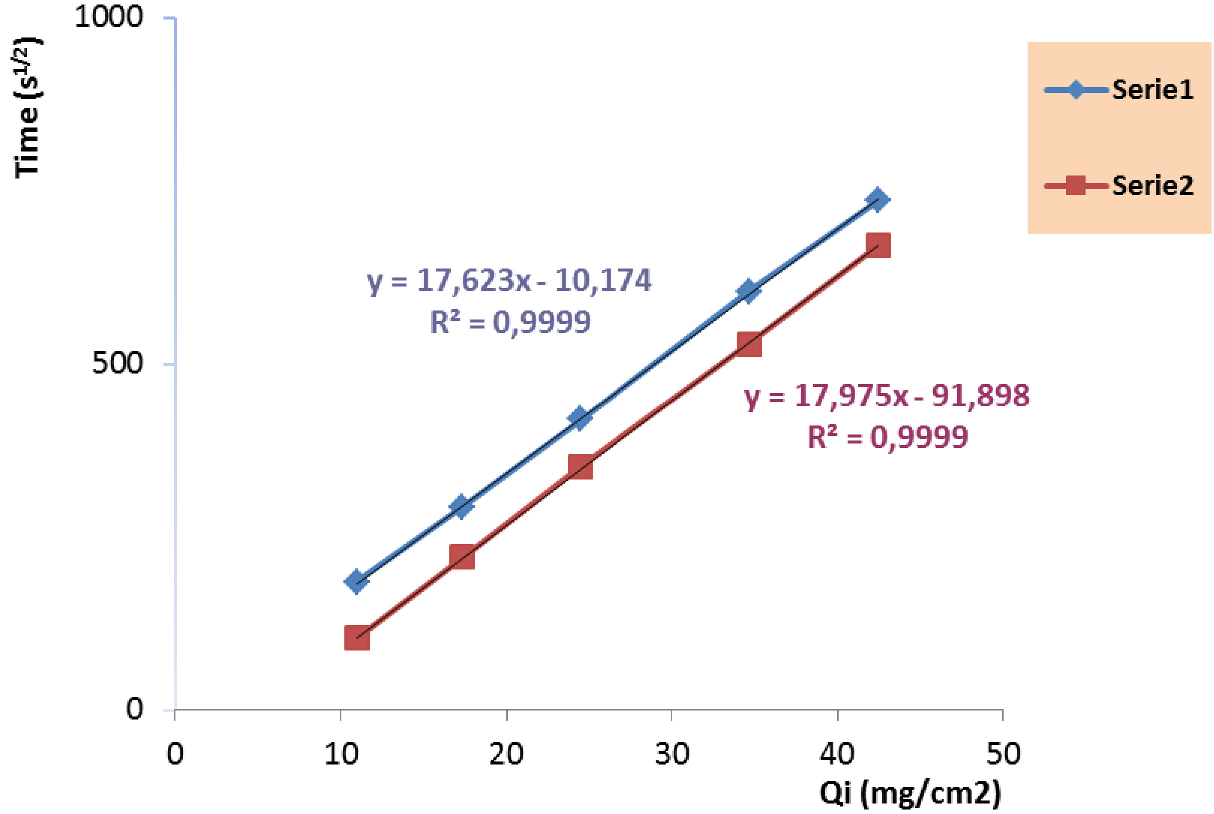


Figure n.97 - Graph of the Q0 value for samples M 80

Mixed 90%

	m_{t0}(g)	h(cm)	d(cm)	r(cm)	Q_0 (mg/cm^2)	A (cm^2)
M90 A	115,97	4,8	4,5	2,25	-53,418	15,90
M90 B	116,88	4,8	4,5	2,25	5,0651	15,90

Table n.39 - Starting data (samples M 90 A and B)

SAMPLE			M90 A			
CA (mg/cm2 √s)			24,3			
t (√s)	t(min)	m(g)	m-m0	Mn-Mn-1	%	Qi(mg/cm^2)
0,00	0,00	115,97	0,000	0,00	0,000%	0,000
10,95	2,00	119,310	3,340	3,34	2,880%	210,112
17,32	5,00	121,820	5,850	2,51	5,044%	368,011
24,49	10,00	124,690	8,720	2,87	7,519%	548,557
34,64	20,00	128,490	12,520	3,80	10,796%	787,607
42,43	30,00	131,510	15,540	3,02	13,400%	977,589
60,00	60,00	137,870	21,900	6,36	18,884%	1377,683
84,85	120,00	141,820	25,850	3,95	22,290%	1626,170
103,92	180,00	142,560	26,590	0,74	22,928%	1672,722
120,00	240,00	143,150	27,180	0,59	23,437%	1709,837
134,16	300,00	143,700	27,730	0,55	23,911%	1744,437
293,94	1440,00	146,540	30,570	2,84	26,360%	1923,095
415,69	2880,00	147,150	31,180	0,61	26,886%	1961,469
509,12	4320,00	147,440	31,470	0,29	0,27136328	1979,7122

Table n.40 - Data from sample M 90 A

SAMPLE				M90 B		
CA (mg/cm2 √s)				23,2		
t (√s)	t(min)	m(g)	m-m0	Mn-Mn-1	%	Qi(mg/cm^2)
0,00	0,00	116,88	0,000	0,00	0,000%	0,000
10,95	2,00	121,030	4,150	4,15	3,551%	261,068
17,32	5,00	123,330	6,450	2,30	5,518%	405,756
24,49	10,00	125,810	8,930	2,48	7,640%	561,768
34,64	20,00	129,590	12,710	3,78	10,874%	799,560
42,43	30,00	132,580	15,700	2,99	13,433%	987,654
60,00	60,00	140,010	23,130	7,43	19,790%	1455,060
84,85	120,00	145,510	28,630	5,50	24,495%	1801,054
103,92	180,00	146,100	29,220	0,59	25,000%	1838,169
120,00	240,00	146,730	29,850	0,63	25,539%	1877,801
134,16	300,00	147,090	30,210	0,36	25,847%	1900,448
293,94	1440,00	148,220	31,340	1,13	26,814%	1971,534
415,69	2880,00	148,410	31,530	0,19	26,976%	1983,487
509,12	4320,00	148,490	31,610	0,08	0,27044832	1988,5193

Table n.41 - Data from sample M 90 B

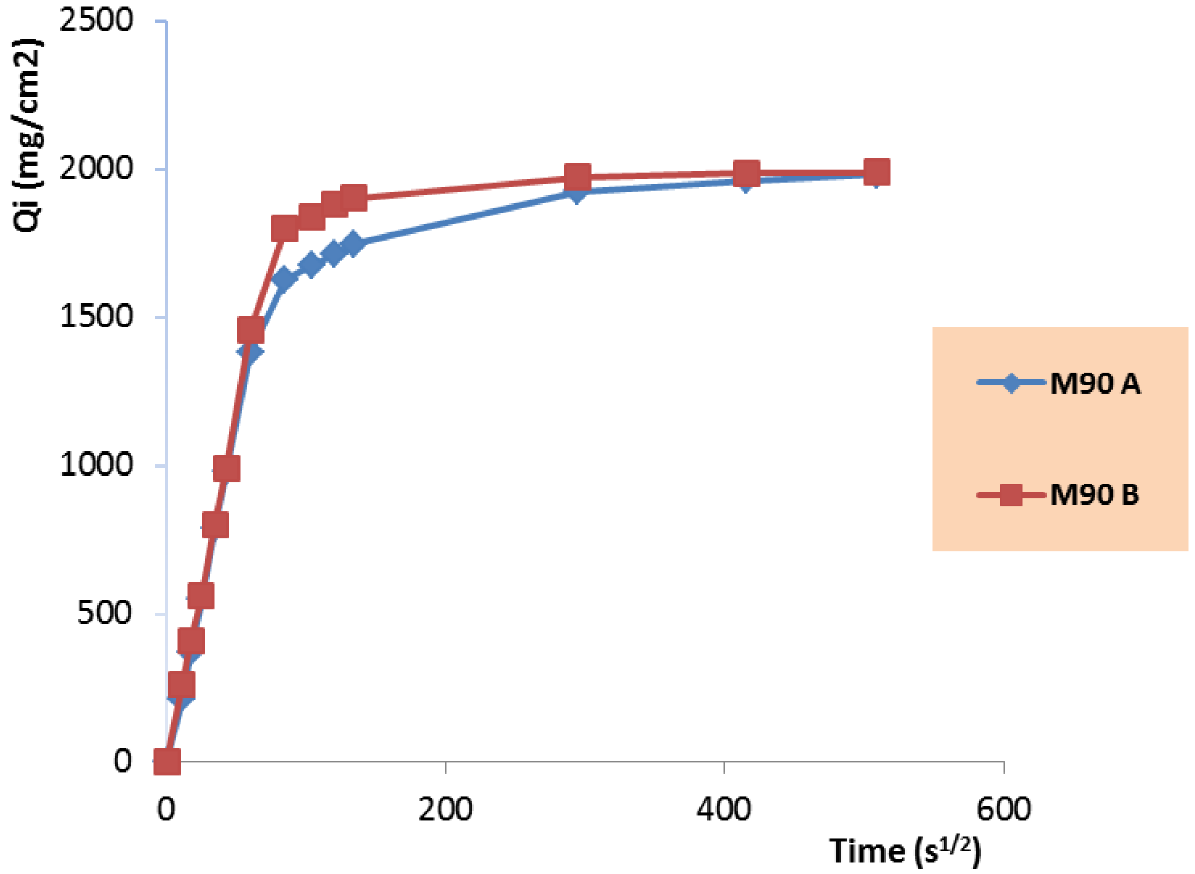


Figure n.98 - Experimental results as quantity of water absorbed (Q) per unit area as a function of time (b) of samples M 90

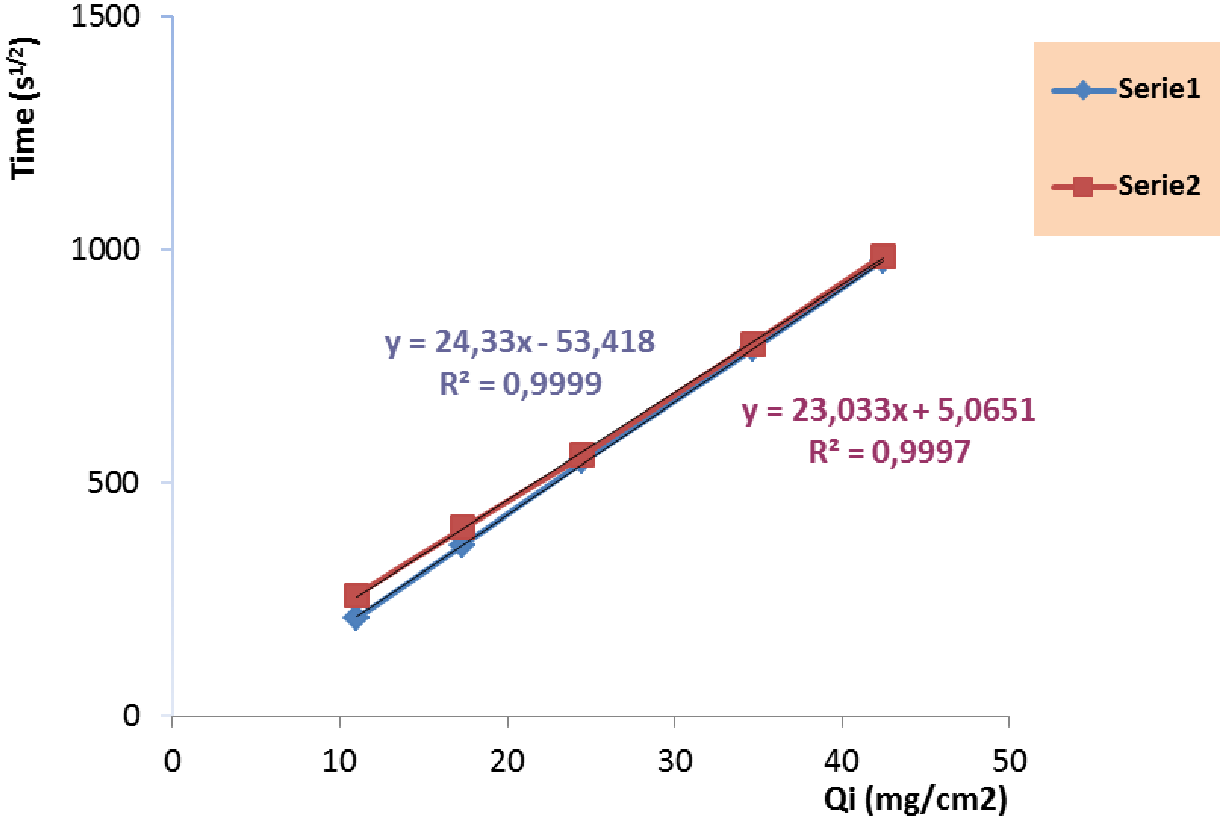


Figure n.99 - Graph of the Q0 value for samples M 90

Mixed 100%

	m_{t0}(g)	h(cm)	d(cm)	r(cm)	Q_0 (mg/cm^2)	A (cm^2)
M100 C	113,43	4,8	4,54	2,27	37,521	16,18
M100 A	105,32	4,52	4,51	2,255	-277,38	15,97

Table n.42 - Starting data (samples M 100 C and A)

SAMPLE			M100 C			
CA (mg/cm2 √s			**27,7**			
t (√s)	**t(min)**	**m(g)**	**m-m0**	**Mn-Mn-1**	**%**	**Qi(mg/cm^2)**
0,00	0,00	113,43	0,000	0,00	0,000%	0,000
10,95	2,00	118,980	5,550	5,55	4,893%	343,014
17,32	5,00	121,770	8,340	2,79	7,353%	515,448
24,49	10,00	125,040	11,610	3,27	10,235%	717,548
34,64	20,00	129,620	16,190	4,58	14,273%	1000,611
42,43	30,00	133,070	19,640	3,45	17,315%	1213,836
60,00	60,00	141,450	28,020	8,38	24,702%	1731,756
84,85	120,00	143,220	29,790	1,77	26,263%	1841,150
103,92	180,00	143,490	30,060	0,27	26,501%	1857,837
120,00	240,00	143,890	30,460	0,40	26,854%	1882,559
134,16	300,00	144,070	30,640	0,18	27,012%	1893,684
293,94	1440,00	144,970	31,540	0,90	27,806%	1949,307
415,69	2880,00	144,820	31,390	-0,15	27,673%	1940,037
509,12	4320,00	144,750	31,320	-0,07	0,27611743	1935,71043

Table n.43 - Sample data M 100 C

	SAMPLE				M100 A	
	CA (mg/cm2 √s)			**30,5**		
t (√s)	**t(min)**	**m(g)**	**m-m0**	**Mn-Mn-1**	**%**	**Qi(mg/cm^2)**
0,00	0,00	105,32	0,000	0,00	0,000%	0,000
10,95	2,00	105,790	0,470	0,47	0,446%	29,436
17,32	5,00	109,860	4,540	4,07	4,311%	284,337
24,49	10,00	113,150	7,830	3,29	7,434%	490,387
34,64	20,00	117,990	12,670	4,84	12,030%	793,513
42,43	30,00	121,540	16,220	3,55	15,401%	1015,847
60,00	60,00	129,600	24,280	8,06	23,054%	1520,638
84,85	120,00	134,130	28,810	4,53	27,355%	1804,349
103,92	180,00	134,310	28,990	0,18	27,526%	1815,622
120,00	240,00	134,180	28,860	-0,13	27,402%	1807,480
134,16	300,00	134,170	28,850	-0,01	27,393%	1806,854
293,94	1440,00	134,900	29,580	0,73	28,086%	1852,573
415,69	2880,00	135,140	29,820	0,24	28,314%	1867,604
509,12	4320,00	135,190	29,870	0,05	0,28361185	1870,73591

Table n.44 - Sample data M 100 A

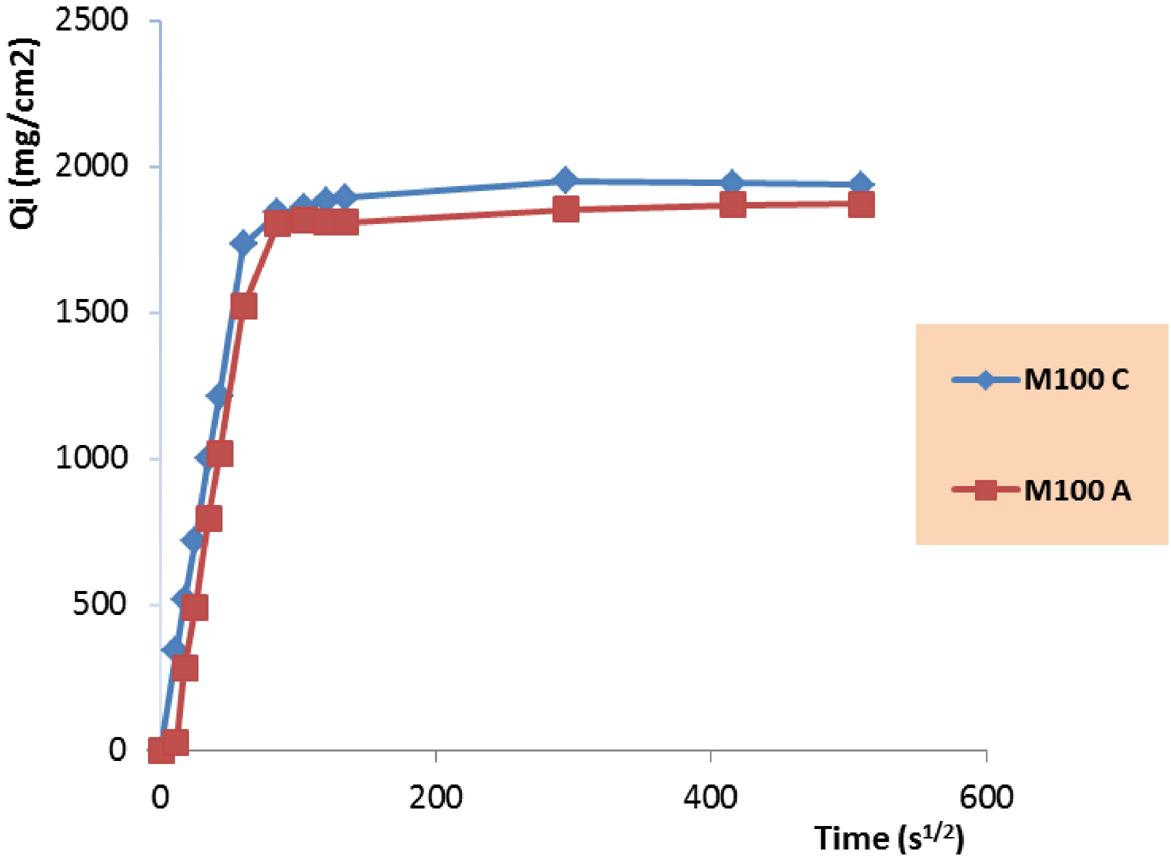


Figure n.100 - Experimental results as the amount of water absorbed (Q) per unit area as a function of time (b) of samples M 100

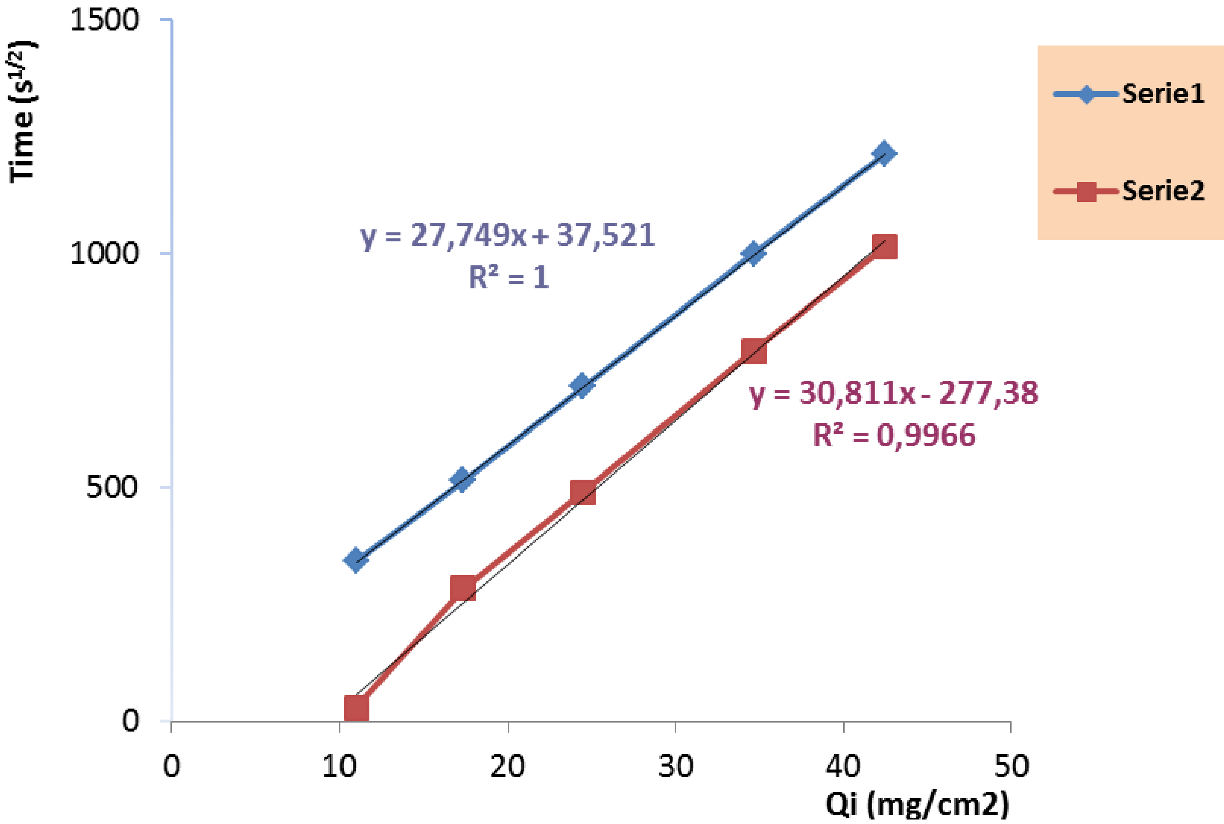


Figure n.101 - Graph of Q0 value for samples M 100

Material	Mixture	CAm	Variance	Sample	CA
C	**10**	7,38	0,03813	C 10 A	7,4
				C 10 B	7,3
	80	17,87	1,25805	C 80 A	19,1
				C 80 B	16,6
	90	19,35	1,71357	C 90 A	21,1
				C 90 B	17,6
	100	15,49	0,39684	C 100 A	15,9
				C 100 B	15,1
CP	**80**	19,53	0,82186	CP80 A	18,7
				CP80 B	20,3
	90	21,89	0,24061	CP90 A	21,6
				CP90 B	22,1
	100	22,25	7,42281	CP100 A	29,7
				CP100 B	14,8
M	**80**	15,61	1,96955	M80 A	17,6
				M80 B	13,6
	90	23,73	0,57061	M90 A	24,3
				M90 B	23,2
	100	29,10	1,37781	M100 A	30,5
				M100 C	27,7

Table n.45 - Summary table

Figure n.102 - Samples subjected to capillary absorption test

Figure n. 103 - Cement-based samples subjected to capillary absorption test

5.3.2 Results of the absorption test

The water absorption by immersion test is useful for assessing the volume mass and the percentage of voids of the materials; for carrying out the test, the indications dictated by the UNI 11060 May 2003 standard were followed. The density is determined as the ratio between the mass of the sample in the dry state and the volume determined by displacement of the densimetric liquid, such as water; the percentage of voids, on the other hand, is a function of

- absolute density: relative to the absolute volume and therefore net of voids;
- actual density: relative to the real volume and therefore considering any closed voids;
- apparent density: related to the apparent volume and therefore including closed and open voids.

The absolute density was determined using the pycnometer method. Firstly, the samples were prepared by drying them in an oven at 65°C for two hours and cooling them in a silica gel desiccator for thirty minutes; then the samples were ground and sieved so that the closed voids were negligible, placed in an oven at 65°C for two hours and stored in a desiccator.

Figure n.104 - Preparation of the test sample (Pycnometer method)

Once the test sample had been prepared, the dry pycnometer was weighed complete with its cap (m_p); the ground sample was then introduced into the pycnometer and reweighed (m_1). At the end of the two weighing, a quantity of water was added to completely cover the sample and the instrument, thus filled and complete with its cap, was placed in a vacuum dryer for about thirty minutes. More water was then added to the inside of the pycnometer and it was left, without the cap, in a temperature-controlled environment for about an hour; at the end it was weighed again (m_2).

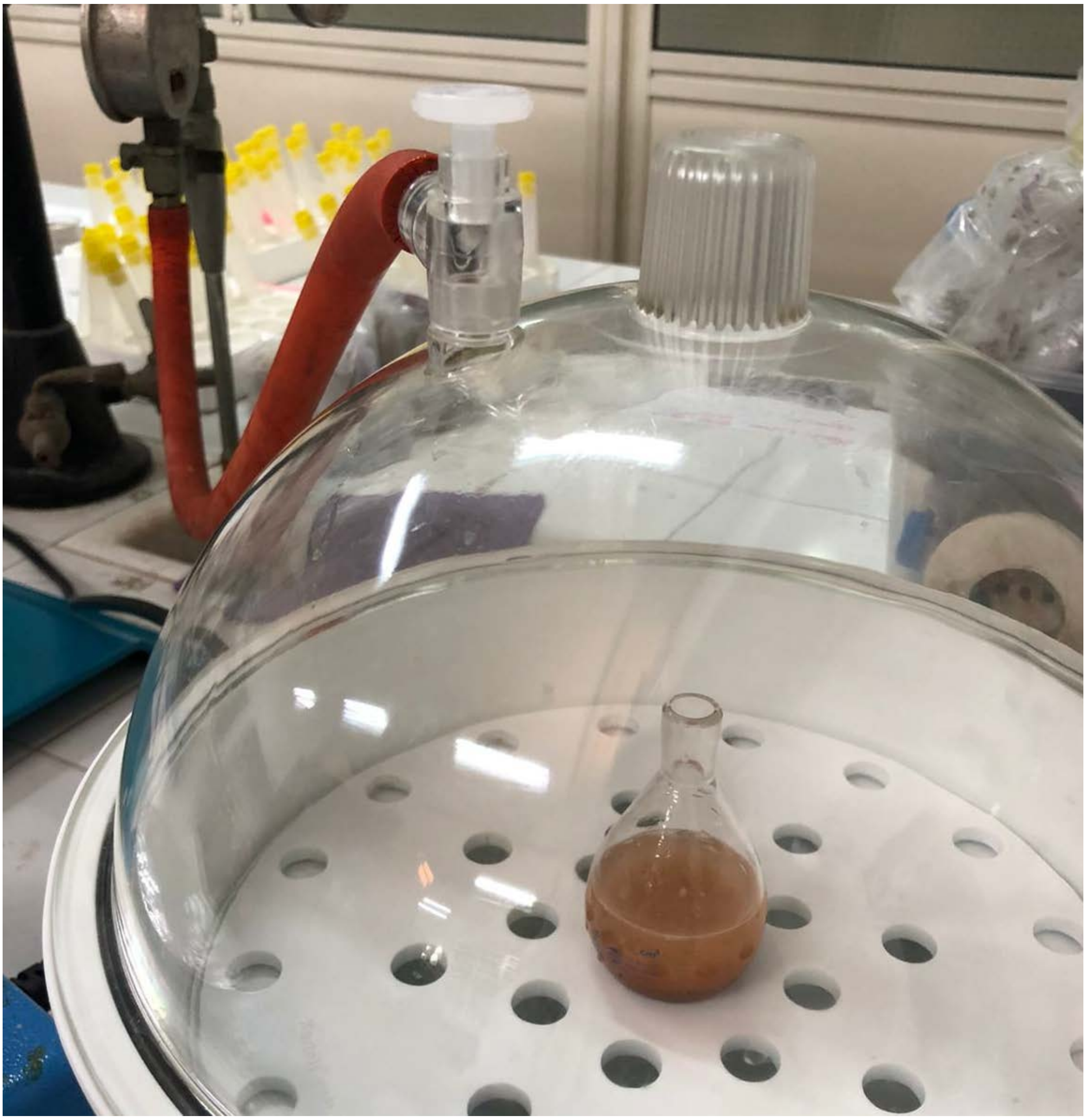


Figure n.105 - Sample subjected to the pycnometer method

At the end of this phase, the pycnometer is weighed again.

The absolute density is then determined as:

$$\rho_{ass} = \frac{(m_1 - m_p) x \rho_L}{V_p \; x \; \rho_L - (m_2 - m_1)} \qquad (4)$$

Where:

- m_p is the mass of the empty pycnometer complete with stopper;
- m_1 is the mass of the pycnometer with the sample;
- m_2 is the mass of the pycnometer with sample and water;
- V_p represents the volume of the pycnometer;
- ρ_L is the density of the water calculated with the pycnometer as the ratio of the difference between the mass of the pycnometer with and without water and its volume.

Then, the apparent volume and the real volume of the samples were determined after they had been dried in an oven until they reached a constant mass.

Sample	Initial weight	Weighing 1	Weighing 2	Weighing 3	Weighing 4
C 80 A	205,06 g	184,50 g	184,68		
C 80 B	199,45 g	181,34 g	181,45		
C 90 A	210,10 g	191,12 g	191,42		
C 90 B	204,73 g	185,77 g	185,99		
CP 80 A	241,17 g	210,58 g	210,27 g		
CP 80 B	241,03 g	210,06 g	209,88 g		
CP 90 A	242,37 g	209,04 g	208,37 g		
CP 90 B	240,03 g	206,94 g	206,50 g		
M 80 A	207,46 g	180,04 g	179,82 g	179,67 g	179,73 g
M 80 B	218,54 g	185,96 g	185,62 g	185,51 g	185,59 g
M 90 A	203,62 g	178,36 g	178,30 g	178,22 g	177,90 g
M 90 B	207,64 g	180,60 g	180,37 g	180,38 g	180,17
T 80 A	187,21 g	166,32 g	165,91 g	165,67 g	
T 80 B	181,87 g	163,11 g	162,75 g	162,47 g	

Table n.46 - Summary of some samples dried to constant mass

The determination of saturated mass and saturated mass determined by hydrostatic weighing was then carried out.

First, the vacuum dryer was filled with a sufficient quantity of densimetric liquid, such as water, so that the samples were covered with a head of at least 5 mm; then the dried samples were placed inside the dryer, suitably spaced to allow the air bubbles developed by the open voids to flow easily. The vacuum was induced for about two hours and at the end all the samples were weighed to determine the saturated mass (m_s). The samples thus saturated were then subjected to hydrostatic weighing by placing them in the sample holder basket immersed in a container containing the same densimetric liquid and hooked to the balance as shown in figure n.29. Once equilibrium was reached on the balance, the values of the mass of the basket with the saturated sample were recorded (m_h).

Sample	**m_{sec}**	**m_{sat}**	**$m_{sat,idr}$**
C 80 A	184,68 g	228,76 g	102,75 g
C 80 B	181,45 g	222,98 g	99,78 g
C 90 A	191,42 g	228,94 g	107,22 g
C 90 B	185,99 g	224,18 g	104,32 g
C 100 1	183,48 g	240,67 g	114, 89 g
C 100 2	184,53 g	243,17 g	115,52 g
CP 80 A	210,27 g	242,52 g	123,88 g
CP 80 B	209,88 g	243,65 g	123,79 g
CP 90 A	208,37 g	239,58 g	120,59 g
CP 90 B	206,50 g	237,61 g	119,10 g
CP 100 C	204,37 g	244,77 g	127,22 g
CP 100 B	204,81 g	245,22 g	126,21 g
M 80 A	179,73 g	222,09 g	105,00 g
M 80 B	185,59 g	230,93 g	108,26 g
M 90 A	177,90 g	230,34 g	110,53 g
M 90 B	180,17 g	232,36 g	112,41 g
M 100 A	168,54 g	225,70 g	103,60 g
M 100 B	168,30 g	225,52 g	103,60 g
T 80 A	165,67	/	/
T 80 B	162,47	/	/

Table n.47 - Summary of values of saturated mass and basket mass with saturated sample by hydrostatic weighing

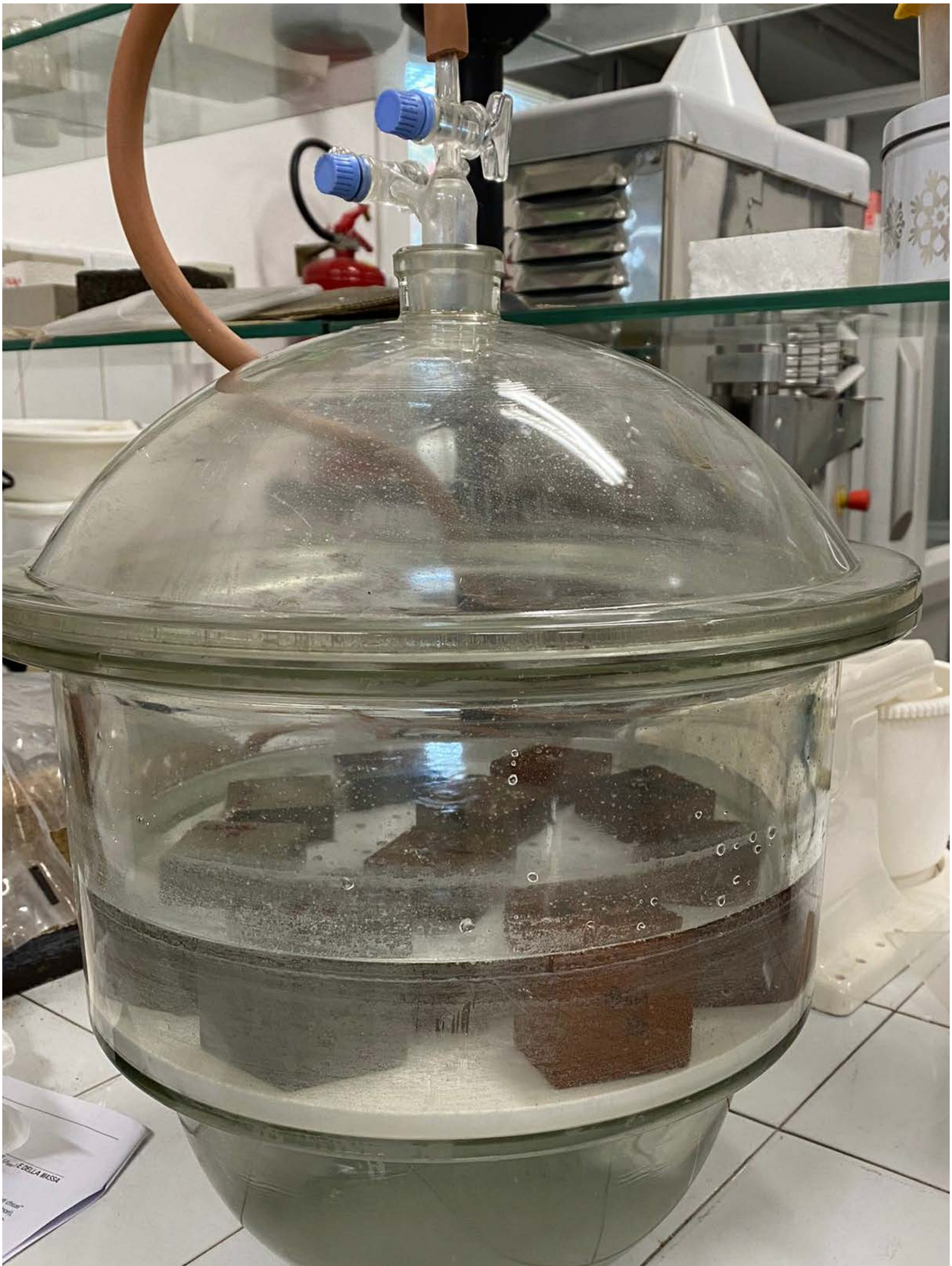


Figure n.106 - Samples subjected to the absorption test by immersion

Figure n.107 - Samples subjected to the immersion absorption test (determination of saturated mass in a vacuum desiccator)

At this point, the following calculations were carried out:

- real (5) and apparent (6) volume;
- real (7) and apparent (8) density;
- percentage of open voids (9);
- percentage of absorption (10).

The values were determined according to the following formulas:

$$V_r = V_{app} - \frac{(m_s - m_d)}{\rho_L} \tag{5}$$

$$V_{app} = \frac{m_s - (m_h - m_{0,h})}{\rho_L} \tag{6}$$

$$\rho_r = \frac{m_d}{V_r} \tag{7}$$

$$\rho_{ass} = \frac{m_d}{V_{app}} \tag{8}$$

$$\%VA = \frac{\rho_r - \rho_{app}}{\rho_r} \tag{9}$$

$$\%A_{H2O} = \frac{(m_s - m_d)}{m_s} \tag{10}$$

where:

- m_d is the mass of the dried sample;
- m_s is the mass of the saturated sample;
- m_h is the mass of the basket with the saturated sample determined by hydrostatic weighing;
- $m_{0,h}$ is the mass of the empty basket determined by hydrostatic weighing;
- ρ_L is the density of water.

The tabulated results of the calculated values are shown below.

Sample	Vapp ml	Vapp ml	Apparent density g/ml	Apparent density g/ml
CP 80 A	118,64	119,25	1,77	**1,76**
CP 80 B	119,86		1,75	
CP 90 A	118,99	118,75	1,75	**1,75**
CP 90 B	118,51		1,74	
CP 100 C	117,55	118,28	1,74	**1,73**
CP 100 B	119,01		1,72	
C 80 A	126,01	124,61	1,47	**1,47**
C 80 B	123,20		1,47	
C 90 A	121,72	120,79	1,57	**1,56**
C 90 B	119,86		1,55	
C 100 A	125,78	126,72	1,46	**1,45**
C 100 B	127,65		1,45	
M 80 A	117,09	119,88	1,53	**1,52**
M 80 B	122,67		1,51	
M 90 A	119,81	119,88	1,48	**1,49**
M 90 B	119,95		1,50	
M 100 A	122,10	122,01	1,38	**1,38**
M 100 B	121,92		1,38	

Table n.48 - Volume and apparent density of samples

Sample	Vr ml	Vr ml	Actual density g/ml	Actual density g/ml
CP 80 A	86,39	86,24	2,43	**2,44**
CP 80 B	86,09		2,44	
CP 90 A	87,78	87,59	2,37	**2,37**
CP 90 B	87,40		2,36	
CP 100 C	77,15	77,88	2,65	**2,63**
CP 100 B	78,60		2,61	
C 80 A	81,93	81,80	2,25	**2,24**
C 80 B	81,67		2,22	
C 90 A	84,20	82,94	2,27	**2,28**
C 90 B	81,67		2,28	
C 100 A	68,59	68,80	2,68	**2,67**
C 100 B	69,01		2,67	
M 80 A	74,73	76,03	2,41	**2,40**
M 80 B	77,33		2,40	
M 90 A	67,37	67,57	2,64	**2,65**
M 90 B	67,76		2,66	
M 100 A	64,94	64,82	2,60	**2,60**
M 100 B	64,70		2,60	

Table n.49 - Actual volume and density of samples

Sample	Open porosity %	Open porosity m %	H2O absorption %	H2O absorption %
CP 80 A CP 80 B	27,18 28,17	**27,68**	15,34 16,09	**15,71**
CP 90 A CP 90 B	26,23 26,25	**26,24**	14,98 15,07	**15,02**
CP 100 C CP 100 B	34,37 33,96	**34,16**	19,77 19,73	**19,75**
C 80 A C 80 B	34,98 33,71	**34,35**	23,87 22,89	**23,38**
C 90 A C 90 B	30,82 31,86	**31,34**	19,60 20,53	**20,07**
C 100 A C 100 B	45,47 45,94	**45,70**	31,17 31,78	**31,47**
M 80 A M 80 B	36,18 36,96	**36,57**	23,57 24,43	**24,00**
M 90 A M 90 B	43,77 43,51	**43,64**	29,48 28,97	**29,22**
M 100 A M 100 B	46,81 46,93	**46,87**	33,91 34,00	**33,96**

Table n.50 - Open porosity and absorption of samples

5.4. Results of the mechanical test

The results reported in the following paragraphs relate to the mechanical resistance tests under flexion and compression stress and to the surface hardness tests. The mechanical strength tests were carried out in the materials laboratory TEMA Lab of the Escuela Técnica de Edificacion of the Universidad Politécnica de Madrid.

5.4.1 Results of the flexural and compressive strength test

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 (see table n.51). 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.

Sample	Reference	Density (kg/m^3)	R_F (MPa)	R_C (MPa)
100% CP		1390	2.85	5.34
Lightweight gypsum	[126]	910	1.52	2.17
Metakaolin-based foam	[127]	1000	0.14	4.62
Diatomite-based foam	[128]	423	0.63	1.49
NHL	[129]		2.15	5.55
NHL+2%glass fibres	[129]	1590	2.41	3.62
NHL with plastic waste aggregate	[130]	1670	0.60	1.25
Dredged sediments geocomposite	[119]	/	/	1.90
Cement mortar with mixed recycled aggregate	[131]	1660	2.38	5.20
Gypsum + 1% polystyrene waste	[132]	970	2.89	5.64
Gypsum Plaster with ceramic waste from bricks	[133]	1180	2.80	5.40
Gypsum composites with glass waste	[134]	1270	2.93	6.01
Gypsum plaster with hemp fibres	[135]	/	2.50	/

Table n.51 - Comparison with results from other references

Based on these results, it was decided to proceed with the production of other mixtures containing a higher fraction of inert aggregate and a percentage of flyash. The addition of these two elements served to improve the mechanical properties in the hardened state and the workability in the fluid state.

Table n.52 below shows the results obtained in accordance with UNE EN132279-1:2009, during the flexural and compressive strength tests.

Sample	Flexural strength (N/mm2)		Compressive strength (N/mm2)			
	Load max (kN)	Strength max (MPa)	Load max A (kN)	A (MPa)	Load max B (kN)	B (MPa)
M 80+50 1	1,445	3,386	12,55	7,84	11,19	6,99
M 80+50 2	1,150	2,695	12,04	7,52	12,03	7,52
M 90+50 1	1,059	2,481	10,03	6,27	9,66	6,04
M 90+50 2	1,173	2,749	9,42	5,89	8,36	5,23
M 100+ 50 1	0,919	2,155	7,24	4,52	6,69	4,18
M 100+ 50 2	0,84	1,97	6,2	3,87	6,7	4,19
T 80+50 1	0,546	1,279	1,94	1,21	2,14	1,34
T 80+50 2	0,501	1,174	1,42	0,88	1,53	0,96
CP 80+50 1	1,930	4,524	21,61	13,51	20,57	12,85
CP 80+50 2	1,170	2,742	13,73	8,58	21,1	13,19
CP 80+50 3	1,980	4,640	18,76	11,72	25,86	16,16
CP 90+50 1	2,222	5,209	27,16	16,98	23,96	14,98
CP 90+50 2	1,409	3,303	23,86	14,91	20,49	12,81
CP 90+50 3	1,661	3,894	18,32	11,45	23,03	14,39
CP 100+50 1 CP 100+50 2 CP 100+50 3	Broke					
C 80+50 1	1,091	2,556	8,16	5,1	7,97	4,98
C 80+50 2	1,104	2,587	7,77	4,86	7,91	4,95
C 90+50 1	0,604	1,415	3,73	2,33	4,8	3
C 90+50 2	0,813	1,905	5,14	3,21	5,66	3,54
C 100+50 1	0,741	1,737	3,96	2,48	5,04	3,15
C 100+50 2	0,793	1,859	4,34	2,71	4,46	2,79

Table n.52 - Results of flexural and compressive strengths

The average flexural and compressive strength values for each mixture are also shown:

Mixture	Flexural strength (N/mm2)	Compressive strength (N/mm2)
M 80 + 50	3,04	7,47
M 90 + 50	2,62	5,86
M 100 + 50	2,06	4,19
T 80 + 50	1,23	1,10
CP 80 + 50	3,97	12,67
CP 90 + 50	4,14	14,25
C 80 + 50	2,57	4,97
C 90 + 50	1,66	3,02
C 100 + 50	1,80	2,78

Table n.53 - Average values of bending and compressive strengths

The following table contains the density values obtained as an average of the density values of the three samples for each mixture:

Mixture	Density (Kg/m3)
M 80 + 50	1644
M 90 + 50	1581
M 100 + 50	1485
T 80 + 50	1391
CP 80 + 50	1824
CP 90 + 50	1776
CP 100 + 50	1824
C 80 + 50	1668
C 90 + 50	1666
C 100 + 50	1595

Table n.54 - Average density values

Figure n.108 - Samples subjected to the flexural strength test
(C 100 +50 - M 100 +50)

Figure n.109 - Samples subjected to the flexural strength test
(T 80 +50 - C 80 +50)

Figure n.110 - Samples subjected to the flexural strength test
(M 90 +50 - CP 90 +50)

Figure n.111 - Sample subjected to the compressive strength test

Figure n.112 - Sample tested for compressive strength and previously for flexural strength

5.4.2 Results of the surface resistance test

The results obtained from the Shore D tests shown in Table 55 are for the 3 prisms produced with 100% fine-grained CP. An average surface hardness value of 82.16 was reported, which is comparable to building plasters and gypsum composites [134,132].

Sample	Point 1	Point 2	Point 3	Point 4	Point 5
100% CP 1	85	76	85	86	90
	86	86	72	80	86
100% CP 2	84	86	86	82	89
	76	85	73	81	80
100% CP 3	85	80	75	86	86
	73	81	74	84	87

Table n.55 - Shore D test results for 100% CP

Mixture	Surface hardness
M 80 + 50	74
M 90 + 50	62
M 100 + 50	60
T 80 + 50	61
CP 80 + 50	78
CP 90 + 50	78
C 80 + 50	61
C 90 + 50	57
C 100 + 50	54

Table n.56 - Shore D test results

Figure n.113 - Durometer used for the Shore D surface resistance test

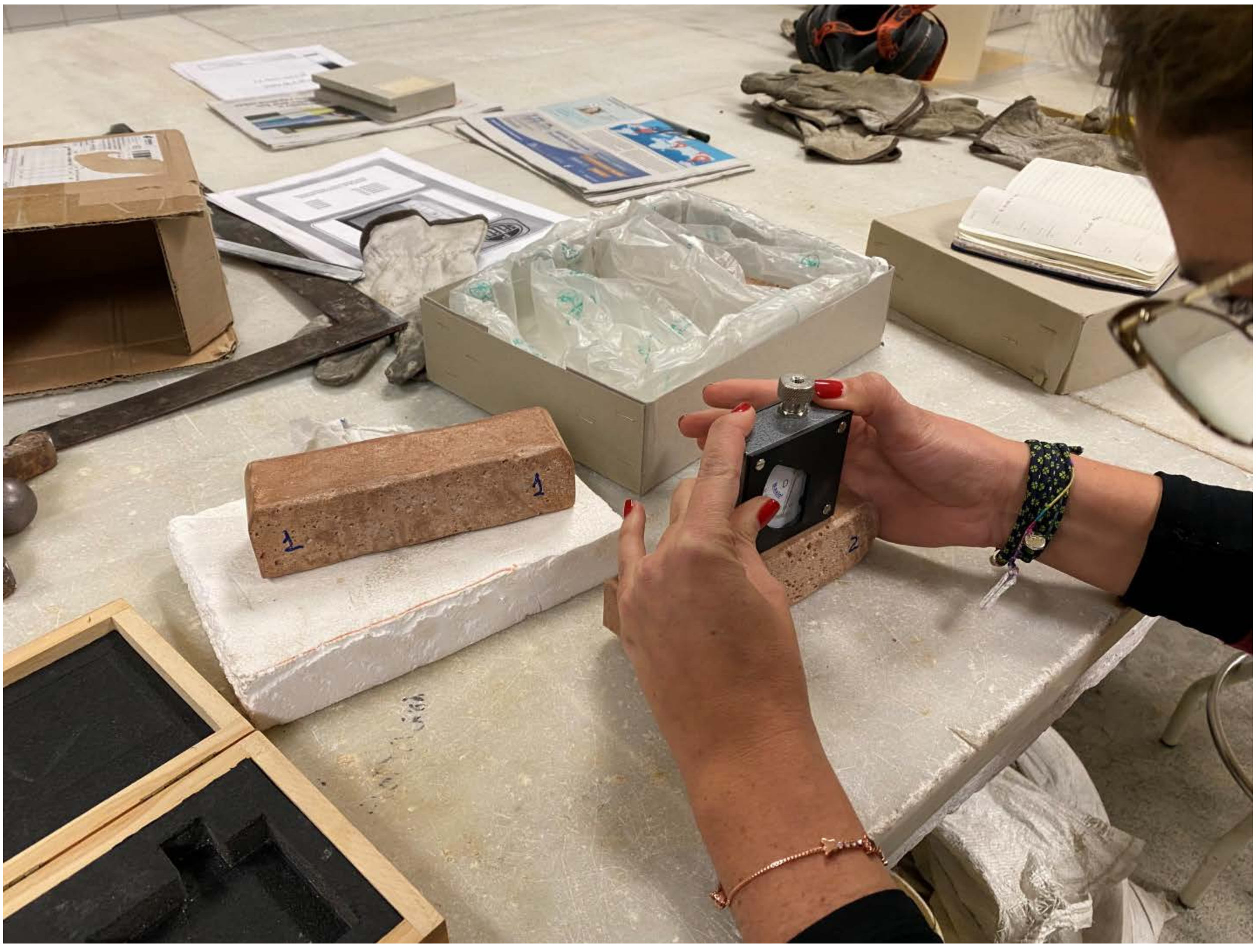


Figure n.114 - Surface strength test on CP samples

Figure n.115 -Test of Shore D surface resistance

5.5. Partial conclusion of the chapter

As has been shown in the previous sections of this chapter, the results for the mixtures based on brick, cement and demolition mixture have been extremely satisfactory; the tuff mixture for high concentrations of material did not produce the expected results, nevertheless it has been shown that from a percentage of 80% a fair level of geopolymerisation is obtained although with a poor resistance to water absorption especially in the immersion tests. Regarding bricks, the results obtained showed that geopolymers produced from crushed bricks, when compared to building materials produced with traditional technologies, are characterised by good properties in terms of open porosity, water absorption and also mechanical strength and surface strength values. The preliminary chemical and mineralogical characterisation performed on the bricks in order to assess whether their chemical compositions could make them suitable for undergoing a geopolymerisation process, confirmed their mainly clayey nature. The geopolymer samples produced were extensively characterised by laboratory tests of chemical-physical, morphological and mechanical properties. In particular, FTIR, XRD and SEM analyses confirmed that geopolymer reactions had indeed taken place. The evaluation of the physical and mechanical properties led to the conclusion that brick waste can be successfully proposed and used as raw materials for the production of prefabricated geopolymer-based components. From the data reported in table n.51, also compared with tables n.53 and n.54 it is possible to deduce that the density and mechanical performance of the samples produced with 100% of CP and those produced with 80% of tuff and 50% of aggregate are very similar to those of the gypsum samples produced with glass waste and also with a ceramic brick waste similar to the cocciopesto used in this work, while all the other values are similar or higher than the values characterising the natural hydraulic lime with glass fibres or the cement mortar with recycled aggregates; these are very interesting results in the evaluation of the thermal conductivity of the materials produced because, as is well-known, thermal inertia is functionally linked to the density of the materials. The average values related to the 100% brick specimens confirm that the mechanical properties are similar to those of a plaster composed with fine or coarse aggregates from ceramic waste, in a quantity of 100% on the weight of the plaster [136]. The average values related to the mixtures reported in table n.53 are very similar to each other, both with regard to flexural strength and compressive strength, with the exception of those related to cocciopesto 80 and cocciopesto 90, which are clearly higher; in fact, the aforementioned CP100% samples with fine grain size and without the addition of flyash also belong to the same range of results. This similitude between the reported values gives the possibility to make a series of global considerations with respect to the possible future applications; in the same way the values of the brick that differ from the others, give the possibility to deepen the potentialities. In the table n.57 a summary of the results of the mechanical tests obtained on the specimens made with the addition of aggregate is reported.

The data of the physical tests demonstrate that the experimental method was performed with high repeatability and that all the samples reached water saturation after 5-6 hours. In addition, the water absorption rate decreased for longer times and this could be related to the increasing water content within the sample and the slow progressive participation of the less accessible pores [137]. The average value of the capillary absorption coefficient is shown in table n.45. It is worth noting that the capillary absorption coefficient obtained for all the geopolymer mixtures turns out to be comparable to the common values of NHL mortars and, at the same time, lower than that of typical solid clay bricks (≈ 26) except for the mixture related to the demolition mixture in the percentage of 100% [138]. Regarding the obtained open porosity value, this has a minimum of 27% in the cements and a maximum of almost 47% in the demolition mixture.

Sample	Volume (cm^3)	Weight (g)	Density (g/cm^3)	Flexural strength (N/mm^2)		Compressive strength (N/mm2)				Surface hardness	
				Load max (kN)	Strength max (MPa)	Load max A (kN)	A (MPa)	Load max B (kN)	B (MPa)	up	down
M 80+50 1	256	420,04	1,641	1,445	3,386	12,55	7,84	11,19	6,99	76,20	75,40
M 80+50 2	256	423,56	1,655	1,150	2,695	12,04	7,52	12,03	7,52	71,80	71,20
M 80+50 3	256	419,15	1,637							74,40	73,20
M 90+50 1	256	399,38	1,560	1,059	2,481	10,03	6,27	9,66	6,04	61,60	66,80
M 90+50 2	256	408,35	1,595	1,173	2,749	9,42	5,89	8,36	5,23	64,80	59,00
M 90+50 3	256	406,69	1,589							62,20	59,40
M 100+50 1	256	375,59	1,467	0,919	2,155	7,24	4,52	6,69	4,18	57,2	52
M 100+50 2	256	381,96	1,492	0,84	1,97	6,2	3,87	6,7	4,19	51,4	54
M 100+50 3	256	382,86	1,496							74,4	73,2

T 80+50 1	256	348,58	1,362	0,546	1,279	1,94	1,21	2,14	1,34	69,00	65,4
T 80+50 2	256	358,78	1,401	0,501	1,174	1,42	0,88	1,53	0,96	53,60	58,00
T 80+50 3	256	360,67	1,409							49,60	70,80
CP 80+50 1	256	459,81	1,796	1,930	4,524	21,61	13,51	20,57	12,85	75,40	87,00
CP 80+50 2	256	479,33	1,872	1,170	2,742	13,73	8,58	21,1	13,19	72,80	74,20
CP 80+50 3	256	461,66	1,803	1,980	4,640	18,76	11,72	25,86	16,16	75,80	84,80
CP 90+50 1	256	459,5	1,795	2,222	5,209	27,16	16,98	23,96	14,98	78,00	84,80
CP 90+50 2	256	457,76	1,788	1,409	3,303	23,86	14,91	20,49	12,81	77,00	82,20
CP 90+50 3	256	446,43	1,744	1,661	3,894	18,32	11,45	23,03	14,39	70,60	77,60
C 80+50 1	256	423,12	1,653	1,091	2,556	8,16	5,1	7,97	4,98	68,00	56,00
C 80+50 2	256	430,53	1,682	1,104	2,587	7,77	4,86	7,91	4,95	61,00	59,00
C 80+50 3	256	427,57	1,670							63,00	60,00
C 90+50 1	256	427,83	1,671	0,604	1,415	3,73	2,33	4,8	3	53,00	58,00
C 90+50 2	256	420,84	1,644	0,813	1,905	5,14	3,21	5,66	3,54	55,40	53,20
C 90+50 3	256	430,75	1,683							59,80	59,60
C 100+50 1	256	407,1	1,590	0,741	1,737	3,96	2,48	5,04	3,15	53,60	50,60
C 100+50 2	256	414,03	1,617	0,793	1,859	4,34	2,71	4,46	2,79	48,00	56,40
C 100+50 3	256	403,57	1,576							56,40	59,80

Table n.52 - Summary table of results on samples with aggregate

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CHAPTER 6 Applications and future research agendas

The production of geopolymers represents one of the most innovative possibilities to reuse different types of solid waste, being especially effective when used with aluminosilicate and clay waste. After analysing the potential and eco-compatibility of these new materials produced from construction and demolition waste, it was decided to focus on the applications relating to the recovery of the built heritage and of the territory and its surroundings.

Working on the heritage means not only preserving its historical, cultural and landscape value, but also promoting a unique economic resource, promoting social development and environmental protection. In this sense, the European Union is promoting smart development of environmental, accessibility and sustainability issues with the need to identify "pragmatic" approaches. The direction to follow must therefore aim at the approach of circular economies, considering conservation not only as a limitation, but re-functionalizing and redeveloping spaces in an innovative way without forgetting or erasing the intrinsic value of the territory. [139]

Thanks to the eco-sustainable and chemical-physical properties and to the low cost of the materials used, such as SS, the field of application is very wide; it could concern, for example, the consolidation with injections of compatible material or the covering as prefabricated material or it concerns the large-scale retail trade as a raw-second material.

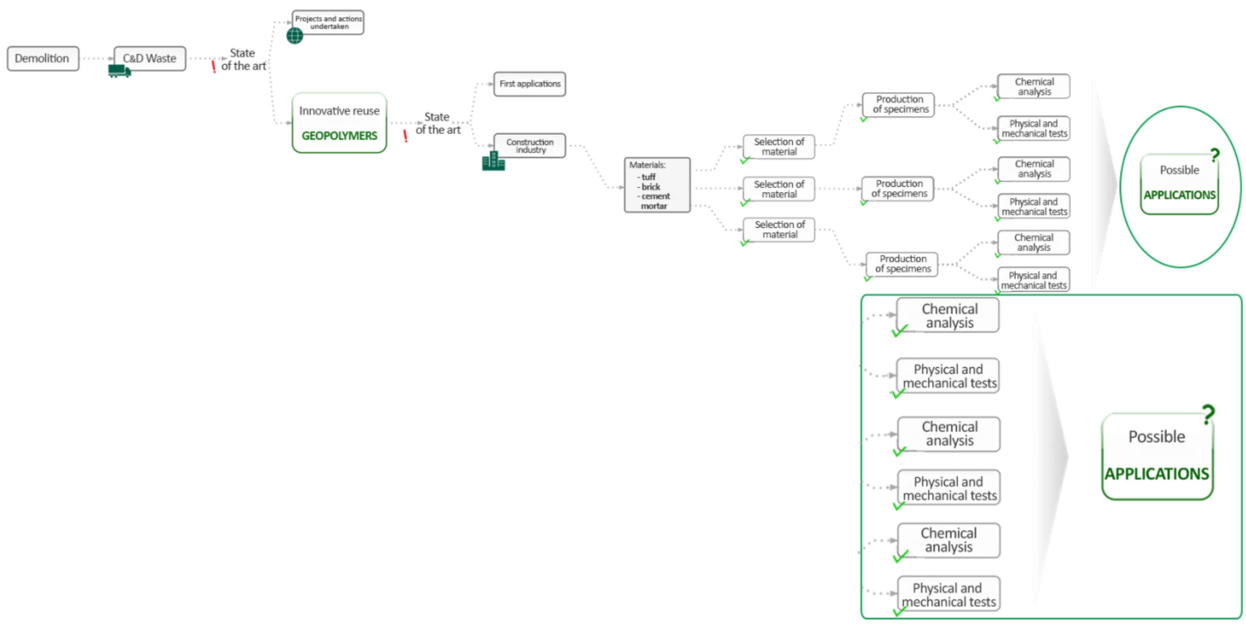

Figure n.116 - Flowchart of research activities related to possible applications

6.1 Re-geopolymerisation tests

One of the questions that emerged during the course of this experimental work concerned the life cycle of the new materials produced. Having identified as the main problem the interception of the enormous flows of materials destined for disposal, an a priori identification of the future actions to be taken in the final phase of the life cycle cannot be ignored.

The production phases of the new cylinder to be subjected to the re-geopolymerisation test are shown below. The production phase of the sample, as well as the immersion phase in bidistilled water, is completely the same as the first phase of production; the difference with the previous samples lies in the use of the powder of the geopolymers produced in the first phase. It is therefore about analysing the ability of a 'third' raw material to geopolymerise a second time and thus be reintroduced into the life cycle once again. The aim is therefore specifically to analyse the potential of a material to be reused over and over again in the production process.

Figure n.117 - Crushing of sample CP 80% for re-geopolymerisation test

Two cylinders were produced, one for brick and one for cement, according to the following formulation valid for the individual sample:

- 50 g powders
- 16,67 g NaOH
- 16,67 g SS

The powder used for the production of the cylinders comes from the first samples produced, which were suitably crushed and sieved to obtain the desired granulometric fraction of < 0.3 mm for the production of the mixture.

Figure n.118 - Re-geopolymerisation test for sample CP 80

Figure n.119 - Sample CP 80 ready to be placed in the oven at 60°C for three days

Figure n.120 - Crushing of sample C 80 for re-geopolymerisation test

Figure n.121 - Mixing of sample C 80 for the re-geopolymerisation test

Figure n.122 - Sample C 80 ready to be placed in the oven at 60°C for three days

Figure n.123 - Sample C 80 re-geopolymerised

Figure n.124 - CP 80 sample after three days in the oven

Figure n.125 – CP 80 sample after re-geopolymerisation test

The test provided satisfactory results for the cement-based sample and less encouraging results for the sample produced with the cocciopesto-based mixture; these results represent a starting point for the possibility of reintroducing the waste material into the production process over and over again. It would be of great interest to continue with the geopolymerisation tests for all the mixtures proposed in this thesis work, proposing in the same way, the tests for the physical characterisation and the mechanical resistance tests on the samples that actually succeed in repeating the geopolymerisation process; these actions would allow to develop a comparative framework with respect to the results obtained that would make it possible to verify the variability of the physical and mechanical performance of the materials produced, as the reuse of the raw materials recovered n-times increases.

6.2 Use of geopolymers as new coatings

One of the fields of application identified concerns the use as an external coating in the form of tiles that can be produced in the desired shape and size, thanks to the fluidity and ease of pouring of the geopolymer thus produced.

The present line of action reserves the right to be deepened and carried on for other mixtures that will be developed in a second phase; in the following paragraphs are shown further tests on the selected mixture of CP 80+50% particularly performing, carried on in the laboratory of materials TEMA of the Departamento de construcciones arquitectónicas y su control of the Escuela Técnica Superior de Edificacion of the Universidad Politécnica de Madrid and some of the first applications of tiles manufactured in the laboratory of materials of the DICMaPI of the University of Naples "Federico II"..

6.2.1 Durability tests

For the durability tests, a further six samples (4x4x16 cm) of the CP 80 +50% brick mix were produced at the materials laboratory of the DICMaPI of the University of Naples "Federico II" and subsequently taken to Madrid for the wet chamber and water/stove cycle tests developed at the TEMA materials laboratory of the Departamento de construcciones arquitectónicas y su control of the Escuela Técnica Superior de Edificacion of the Universidad Politécnica de Madrid.

Figure n.126 - Mould with CP 80 + 50 samples produced for durability testing

Figure n.127 - CP 80 + 50 samples for durability testing

Water/stove cycle

Subjecting the specimens to the water-stove cycle made it possible to determine their capacity to dry and dry out. The test, carried out at the TEMA materials laboratory of the Departamento de construcciones arquitectónicas y su control of the Escuela Técnica Superior de Edificacion of the Universidad Politécnica de Madrid, is not standardised, like the following one, but follows a procedure developed by Mercedes del Rio Merino in her doctoral work in 1999 [140].

Prismatic samples (4x4x16 cm) produced with the CP 80+50% mixture was used. During the test, the samples are completely immersed for two days in a container filled with water, after which the samples are weighed and placed in an oven for two days at a temperature of 45°C. The test involves two cycles of immersion in water and passage in the oven, at the end of which the samples were subjected to the surface hardness test with the Shore D durometer, used as described in the previous chapters. The average value, as can be seen in table 48, is 83; comparing it with that of the CP 80 + 50 samples not subjected to the cycles, which we remember was 78, we can deduce an appreciable behaviour. Similarly, at the end of the two cycles, signs of cracking and the first capillary rise became evident on the samples subjected to the test, as can be seen in the following images.

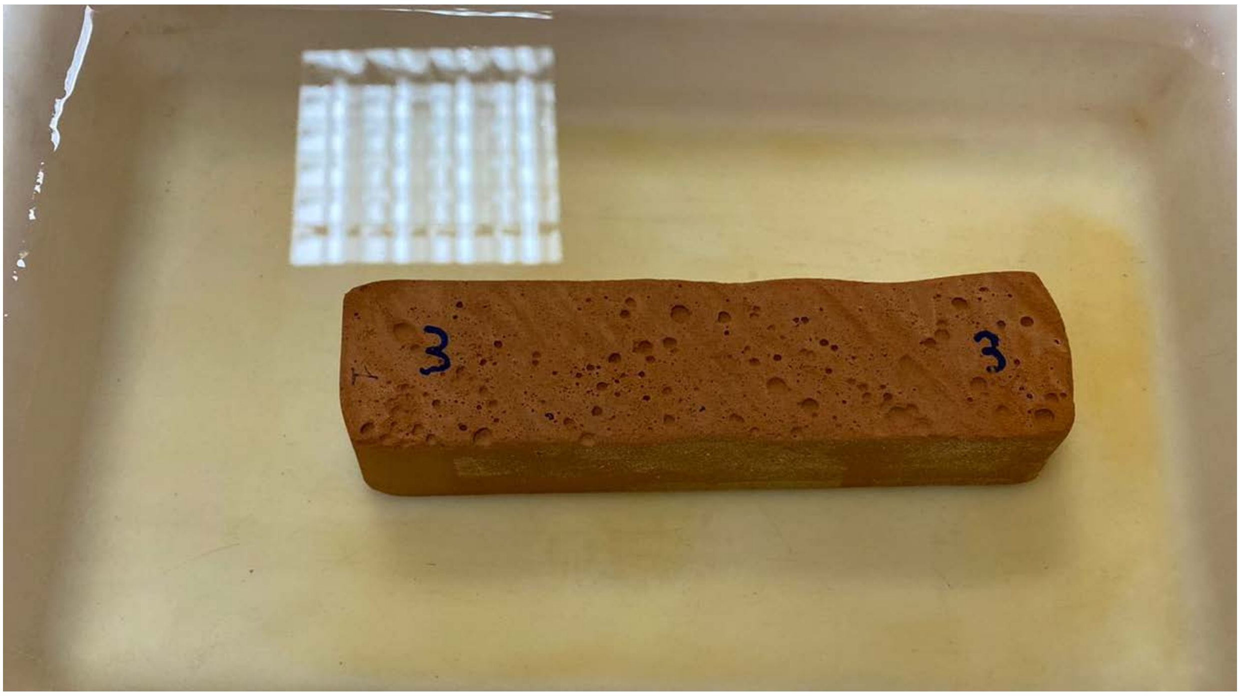

Figure n.128 - CP 80 + 50 sample immersed in water

Weight variation (g)									
Sample	0 h	24 h	48 h	96 h	120 h	144 h	168 h	192 h	216 h
1	479,6	505,5	505,9		441,6		500,3		426,8
2	458,3	484,3	484,4		420,9		478,7		408,5
3	480,9	503,2	503,7		438,7		497,6		421,7

Surface hardness D shore							
		Measurement					
Sample	Side	1	2	3	4	5	V.m
1	a	92	88	86	90	92	83
	b	60	82	85	75	90	
2	a	86	89	86	83	89	
	b	75	75	69	77	82	
3	a	91	86	75	85	89	
	b	74	87	70	92	86	

Table n.53 - Summary table of the results of the cycle in water and in the stove

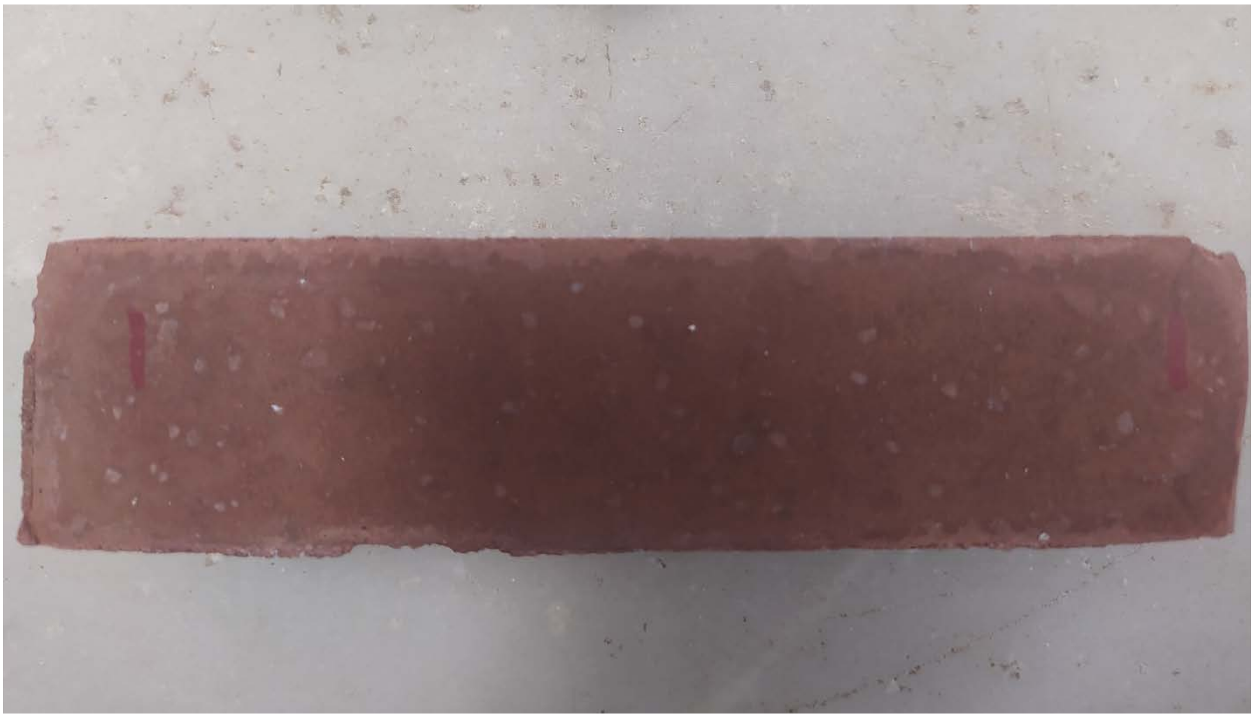

Figure n.129 - Sample 1 CP 80 + 50 matting and efflorescence

Figure n.130 - Samples CP 80 + 50 1, 2 and 3 after the first cycle

Figure n.131 - Capillary rise after the cycle

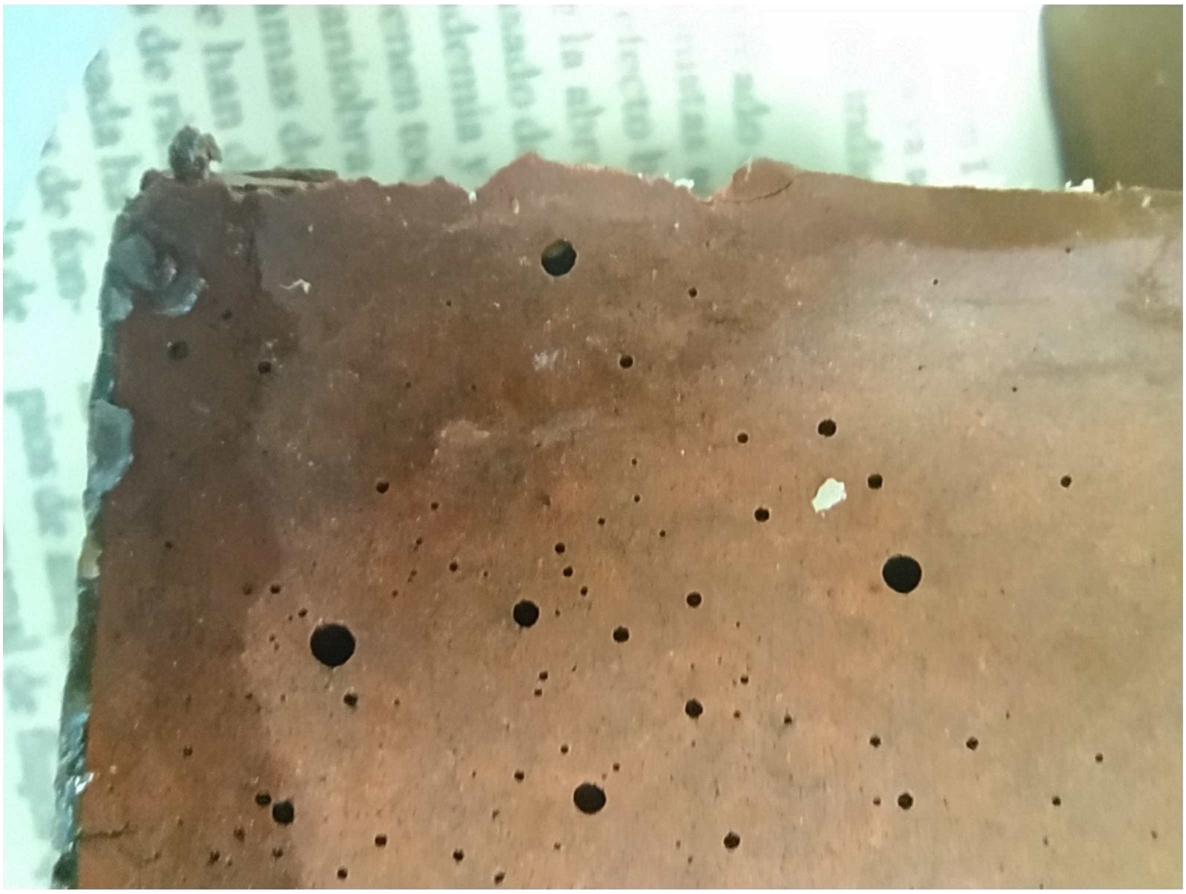

Figure 132 - CP 80 + 50 capillary rise samples

Figure n.133 - Positioning of samples in the oven

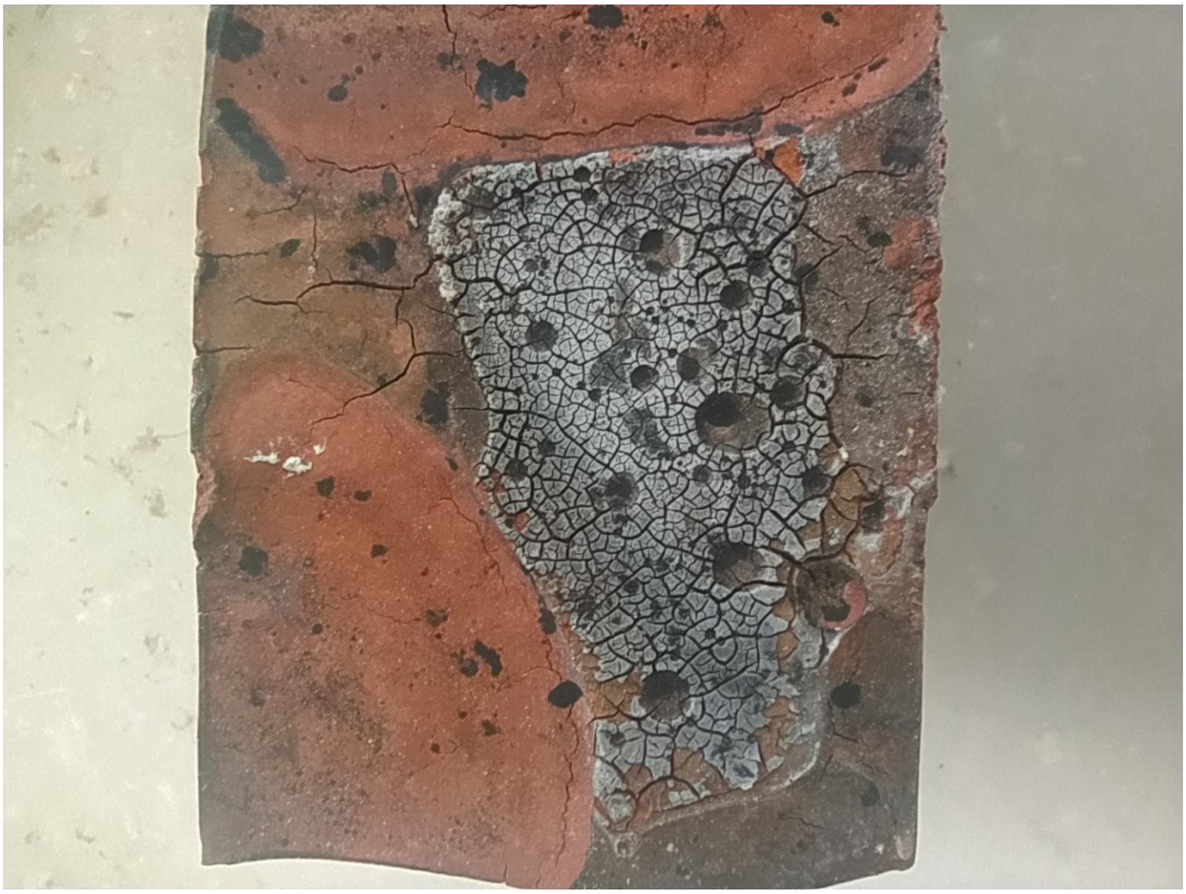

Figure 134 - Samples CP 80 + 50 Matting, cracking and efflorescence

Figure n.135 - Matting and cracking

Figure 136 - Matting, cracking and efflorescence

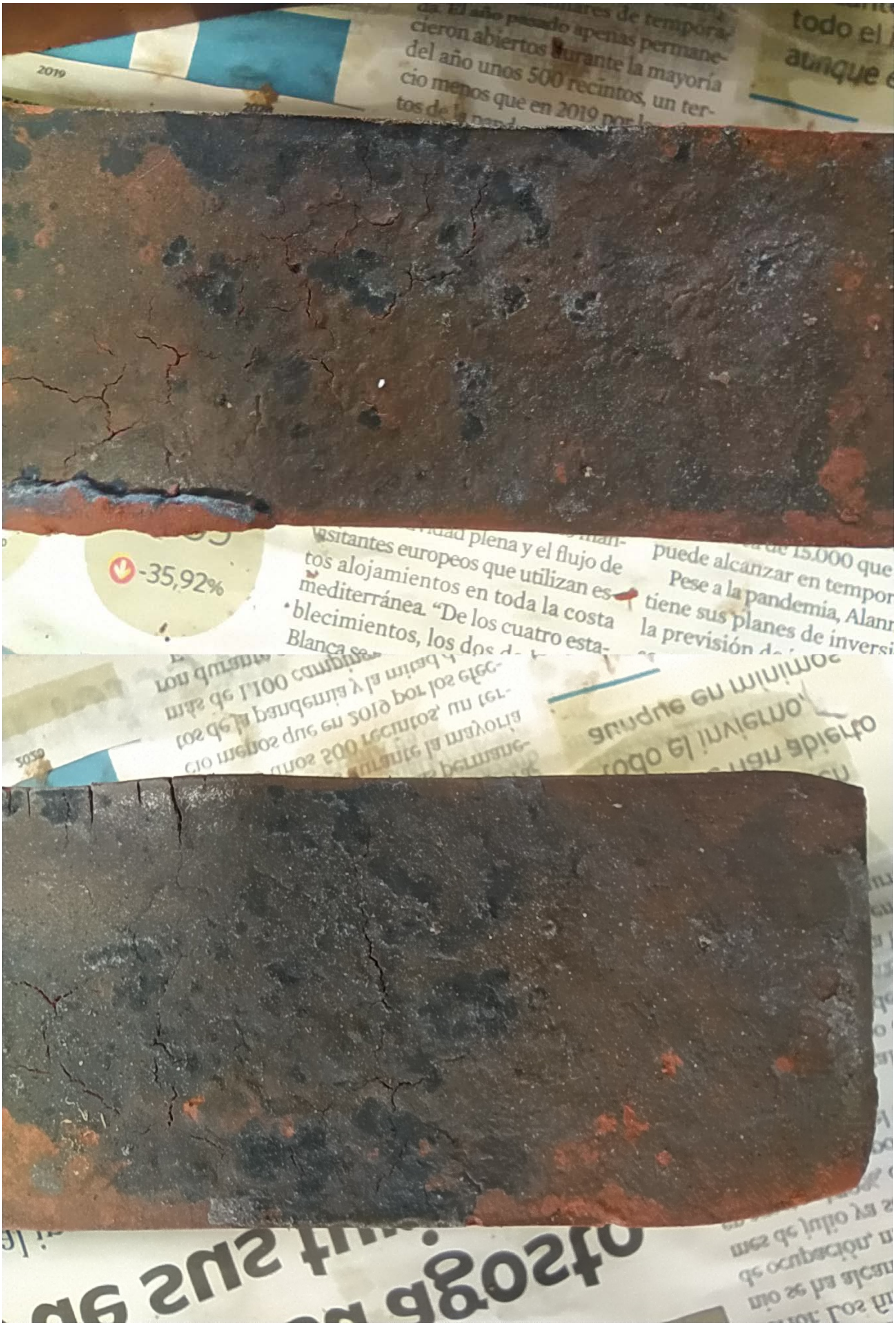

Figure n.137 - Matting and cracking after the cycle

Figure n.138 - Capillary rise of water after immersion

Humid chamber

In order to evaluate the behaviour of the material subjected to constant humidity, three specimens (4x4x16 cm) of CP 80 +50 mixtures were subjected to the wet chamber test developed and perfected by del Rio Merino for his doctoral thesis in 1999. The wet chamber test was carried out at the TEMA materials laboratory of the Escuela Técnica Superior de Edificacion of the Universidad Politécnica de Madrid.

The proposed method evaluates the behaviour of samples that remain for five days in a humid chamber at a temperature of approximately 21°C with a relative humidity value of approximately 72%. At the end of the five days, the samples are extracted from the chamber, weighed and the weight increase is evaluated; after weighing, the samples are left for seven days in natural environmental conditions at a temperature of approximately 21°C with a relative humidity value of 40%. At the end of the seven days, the surface hardness is evaluated by means of the Shore D durometer, which has given similar and comparable results to those of the water-stove cycle test.

Weight variation (g)					
Sample	0 h	24 h	48 h	96 h	120 h
1	504,3	505,9	506,9	511,7	516,1
2	461,7	463,4	464,7	470,1	473,7
3	467,8	469,4	470,4	475	478,5

Surface hardness D shore							
		Measurement					
Sample	Side	1	2	3	4	5	V. m
1	a	55	70	75	86	74	76
	b	80	83	83	69	62	
2	a	84	81	80	81	81	
	b	65	70	80	86	78	
3	a	65	75	84	84	66	
	b	76	77	74	77	83	

Table n.54 - Summary table of the results of the wet chamber

Figure n.139 - Samples CP 80 + 50 inside the wet chamber

Figure n.140 - CP 80 + 50 samples detailing efflorescence after the wet chamber cycle

Figure n.141 - Efflorescence detail after the wet chamber cycle

6.2.2 Tiles production

The following is a first cycle of tile production. The mixture selected for production was the CP 80 +50 brick-based mixture; this, prepared as described above, was cast in wooden moulds. The tiles were produced in the materials laboratory of the DICMaPI of the University of Naples "Federico II".

Figure n.142 - Tile moulds

First tile with coarse-grained waste

Clay brick waste (CBW) was used as raw material for the experimental development of the tiles. The CBW came from the demolition of an old building in the city of Madrid. The waste material was sieved at the TEMA Lab of the Escuela Técnica Superior de Edificacion of the Universidad Politécnica de Madrid and then brought to Naples for the production of the tile at the materials laboratory of the DICMaPI of the University of Naples "Federico II".

Figure n.143 - Material from the demolition of an old building in the city of Madrid

Demolition waste from the city of Madrid was first washed with distilled water (H_2O) and then placed in an oven to dry at a temperature of 60 °C. It was then ground and reduced to the desired grain size for use as aggregate. They were then ground and reduced to the desired grain size for use as aggregate.

The tile was produced with 100% CP in the following quantities:

- 144 g CC
- 48 g NaOH
- 48 g SS

After being poured into a square mould, it was placed in an oven at 60 °C for three days.

Figure n.144 - Material passed through the sieve

Figure n.145 - Crushed and sieved material

Figure n.146 - Preparation of the alkaline solution and the mould


Figure n.147 - Raw materials for the mixture

Figure n.148 - Preparation of the mixture then poured into the mould

Figure n.149 - Mixture poured into the wooden mould

Figure n.150 – Tile in oven at 60°C and after three days

Figure n.151 - First tile produced

Smooth finished tiles

Other waste material from the demolition of an old building located near the city of Naples was used as raw material for the production of other tiles with a smooth finish. The demolished material was ground to a fineness of 0.125-0.150 mm (Fig. 1b).

Figure n.152 - Waste before (a) and after grinding (b)

Figure n.153 - Mix poured into the mould

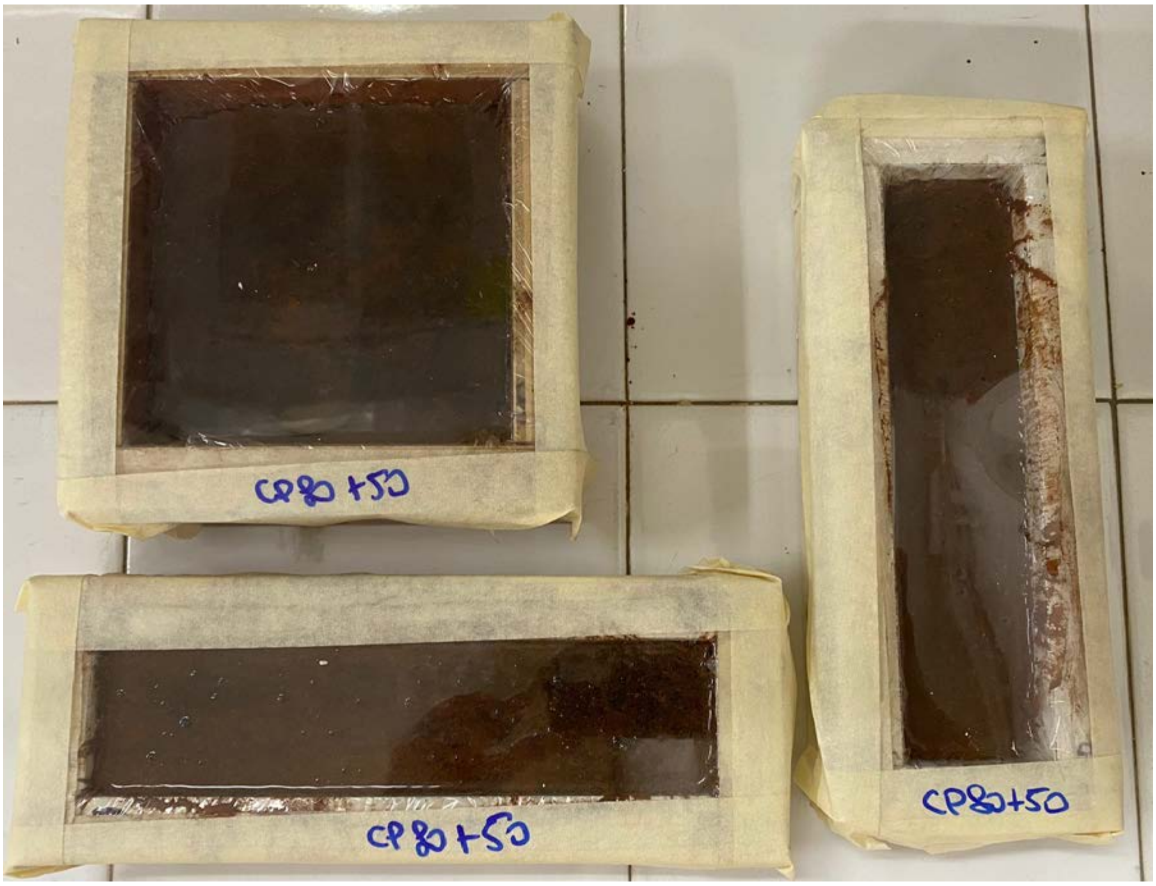

Figure n.154 - Moulds ready for baking at a temperature of 60°C

Figure n.155 - Smooth finish tiles to be rectified

6.2.3 Possible application as a coating: The pilot site of the Farinato High School in Enna

From discussions with companies, institutions and private individuals, it emerged that there is great interest in the use of materials produced in this way. One of the possible applications of the new product as a coating may concern the seismic upgrading worksite of the school building housing the P. Farinato High School in the city of Enna, which could become an excellent example of a pilot worksite being located at an altitude of 930 metres above sea level and in order to assess durability at this altitude, further ageing tests with freeze-thaw cycles may be useful.

The upgrading project was entrusted to a Temporary Grouping of Companies, including the Engineering Company "AIRES Ingegneria" of Caserta, winner of the competition for engineering and architectural services for the design and supervision of the work on the Farinato High School. After a preliminary meeting with the AIRES company, which is responsible for the school's structural design, to assess the possible use of the new geopolymer-based tiles, the possibility of re-using the same cladding materials, which will be removed to carry out the consolidation work, as raw material for the production of the new cladding, emerged. Of the total of 3,700 square metres, the brick cladding to be taken to disposal occupies about two thirds of the surface area and therefore, from the assessment of the costs of demolition and reconstruction or adaptation, emerged the same economic value for which it is evident that the recovery of the waste produced would be of considerable economic advantage.

For these reasons future lines of research should take into account

- the assessment of the production cost;
- the economic advantages in the case of on-site production on site (no waste transport/disposal costs);
- the environmental impact and the reduction of CO_2 emissions by preferring eco-sustainable solutions and km0 production.

Figure n.156 - Farinato High School - Enna

6.3 Potential use of alkali-activated materials in naturalistic engineering

The observation of the relationships that exist between techniques, materials and the geomorphological context tells us the history of places outlines the socio-economic framework and constitutes their identity. The approach to traditional building techniques, together with the definition of local raw materials, is an indispensable tool for understanding, qualifying and distinguishing a civilisation or a historical period. The use of materials present in the territory, which today could be seen as an innovative practice for zero kilometre construction, is instead the starting point; the true zero kilometre of the development of the technique in a particular area [141]. Therefore, starting from geological considerations, it is fundamental to recover a modus operandi of the practice of the past, rethinking it with innovative and sustainable approaches.

The attention to our territory and to local materials, together with the desire to identify an application case that would require technique, tradition, care and innovation at the same time, has led to the choice of the terraces of the Amalfi Coast, declared a cultural landscape in 1997, emblem of culture, tradition and technique, moreover the progressive abandonment of agricultural activities together with the phenomena of hydrogeological instability, have turned on a warning alarm about the approach to their maintenance which cannot and must not follow the procedures of the ordinary building constructions.

The research work was therefore proposed as a declaration of intent to investigate the techniques and the possibilities of using the volcanic materials with pozzolanic activity found in the territory of the Sorrento peninsula, as raw material for the production of mixtures of alkali-activated materials for the renovation and maintenance of dry stone walls. This kind of proposal allows not deviating too much from traditional techniques, while using an innovative and eco-compatible approach. Therefore, the contribution that this line of research wants to give, in response to the problem of hydrogeological risk and to the growing interest in these artefacts, also underlined by the recent National Recovery and Resilience Plan (PNRR) of the Government, is mainly of an operational nature for actions of protection and maintenance of màcere (dry stone walls). This first phase of the research work has seen the selection and analysis of local loose materials, from which good reactivity values in an alkaline environment have emerged. These results lead us to consider the production of alkali-activated binder mixtures to be used, by virtue of their high eco-compatibility, in place of other materials, such as concrete, which is poorly adapted to the peculiarities of the sites, for the production of reinforcing mortars, injections and for the restoration or construction of new màcere.

Figure n.157 - Terraced landscape of the Amalfi Coast

6.3.1 Rehabilitation and maintenance of dry-stone walls on the Amalfi Coast

The Amalfi Coast is characterised, and is universally known, for the particular construction features and morphological peculiarities of the territory with a geomorphological conformation characterised by steep rocky slopes dropping sheer into the sea, and for the succession of terraces which mark out the territory in many ways: landscape, natural, tourist, cultural and social. The horizontal scansion that the terraces create on the rocky slopes adapts to the steepness and morphology of the territory and is achieved through the use of the same rocks present on the sites. This particular system has ensured since the past, and continues to ensure today, the conditions for developing otherwise impracticable crops, mainly lemon trees and vineyards. However, special attention needs to be paid to the maintenance and rehabilitation of individual areas. In fact, the construction of the terraces using the specific technique of the art of dry stone walls has modified the water and morphological structure of the slope that characterised the original natural balance; for this reason, in addition to all the observations relating to the inestimable cultural heritage that these systems represent, it is essential to take constant care of the maintenance of the walls in order to prevent a reconfiguration of the natural morphology and possible situations of instability caused by the progressive abandonment of the terraces. "In this context, knowledge coming from intangible heritage (know-how, traditional knowledge, skills, festivals, etc.) plays a central role in the definition of risk mitigation actions" but, starting from traditional techniques, it is of fundamental importance to define "a new "suitability" based on the assessment and modelling of land degradation and associated danger" [142].

Figure n.158 - Typical landslide involving dry-stone walls on the Amalfi Coast

6.3.2 Regional geomaterial

Rainfall, which has become increasingly intense in recent years, is one of the various natural phenomena which affect and cause damage and inconvenience and which cause flooding and landslides on the slopes [143]. The entire ridge of the Lattari Mountains has been covered over the last few millennia by pyroclastic deposits from the Somma-Vesuvius, which, when saturated by periods of intense and prolonged precipitation, generate fast-flowing landslides with high speed and magnitude and capable of causing extensive damage to structures. In the past, especially during the eruption of 79 a.C., the succession of sedimentation processes of these materials, together with their remobilisation following flow phenomena, led to the formation of reworked volcanoclastic deposits that appear as residual outcrops of several metres thickness and with stone facies, along the narrow river valleys [144 and 146]. These deeply incised deposits are called durece by the local peasants, whose probable Latin origin is *durescere*, i.e. harden, and consist of pumice and ash with a thickness varying from 2 to 10 meters, up to 18 meters in the Positano area and 40 meters in the Valle del Canneto area [144]. Because of its characteristics, the durece is of great value from a sedimentological, geomorphological, hydrogeological and volcanological point of view and is thus classified as a cultural asset of a geological nature [145].

Figure 159 - Outcrop of "Durece" in the Monti Lattari

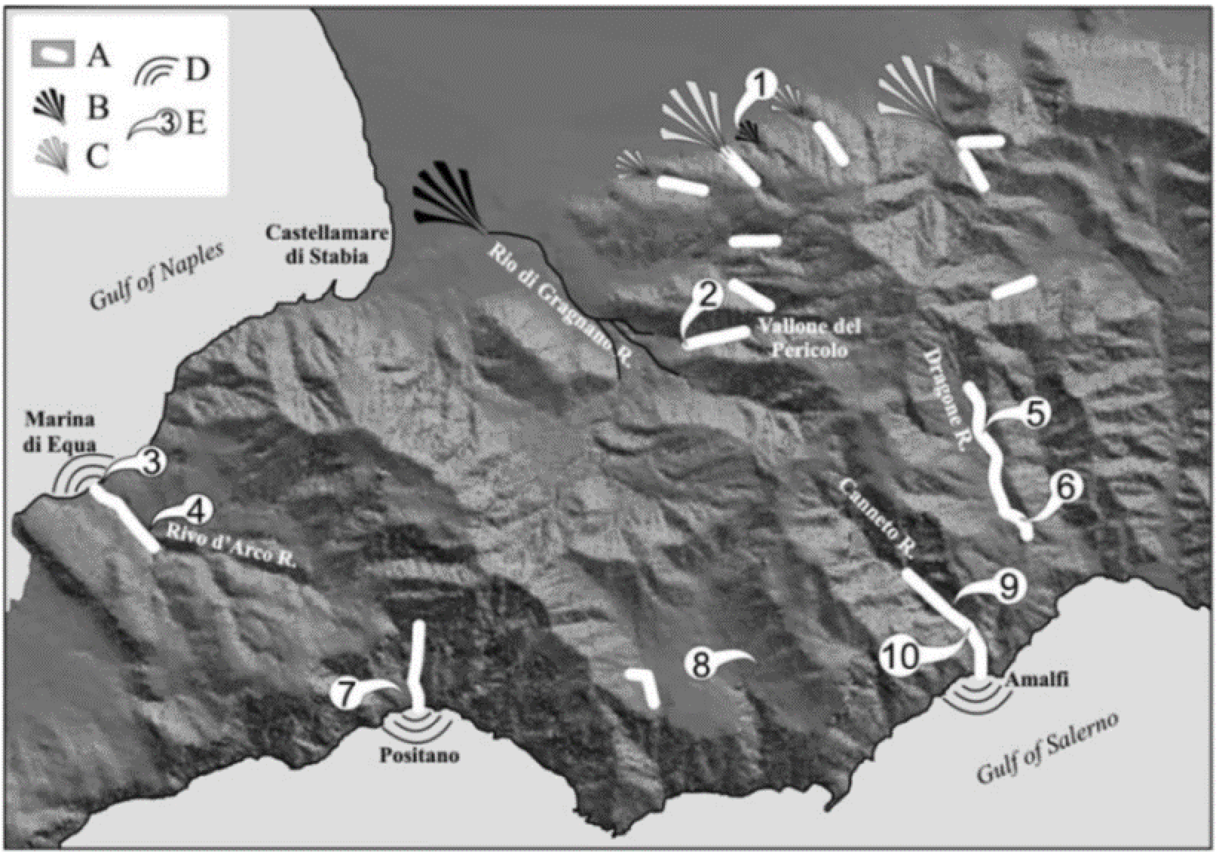

Figure n.160 - Outcrop area of Durece (white) in the main valleys of the Monti Lattari

In addition to the 'durece' and local outcrops of ancient volcanites of Phlegraean origin on the slopes of the study area, pyroclastic products from the fall of the eruption of 79 A.D. are widespread. These have a thickness varying from a few decimetres to 2 meters and are essentially composed of a first layer of 20-40 centimetres of soil of pyroclastic origin, followed by 40-80 centimetres of yellowish cinerites containing small pumices which, only locally, rest on beds of pumices 20-30 cm thick. Finally, a layer of a few decimetres of argillified cinerites covering the fractured and karstified dolomitic limestone substrate is found at depth (Fig. 161) [146].

The presence of loose volcanoclastic deposits covering the Lattari Mountains at a distance of 20 km from the crater is explained by the action of the strong winds that dispersed the materials during the Plinian eruption that destroyed Pompeii. In detail, the cinerites and pumices are of a silicate nature with "very light trachytic and tephritic pumice fragments (predominantly 1-2.5 centimetres in diameter, but with some up to 5 centimetres) with a very subordinate component of scoriaceous and lithic fragments (normally 1 millimetres to a few millimetres in diameter, but sometimes up to 3 centimetres)" [147].

The volcanic eruptions and the consequent fall of the pyroclastic deposits actually allowed the growth of vegetation and the slow formation of soil on the slopes. These slopes can be summarised in three typical aspects, which in turn have conditioned the type of construction of drystone walls. The most widespread type is found in the lower-middle sectors of the dolomitic limestone slopes with slopes between 28 and 35°. In these contexts, dry-stone walls have risen of approximately 2 metres and treads of 3-4 metres. On the other hand, in the foothills of the mountains with a gentle slope (10-25°), pyroclastic deposits are thicker (3-5 metres) and cover ancient bodies of conoids or slope breccias. In these contexts, closer to population centres, the steps between the various terraces can be up to 10 metres long.

Finally, in the mountainous sectors, with greater inclination or along valley incisions, the pyroclastic deposits have been more easily eroded over time. In these contexts, therefore, the rubble is very local and discontinuous, while outcropping fractured limestone abounds, used as small borrow pits for the production of the blocks of rock that form the main structure of the dry-stone walls.

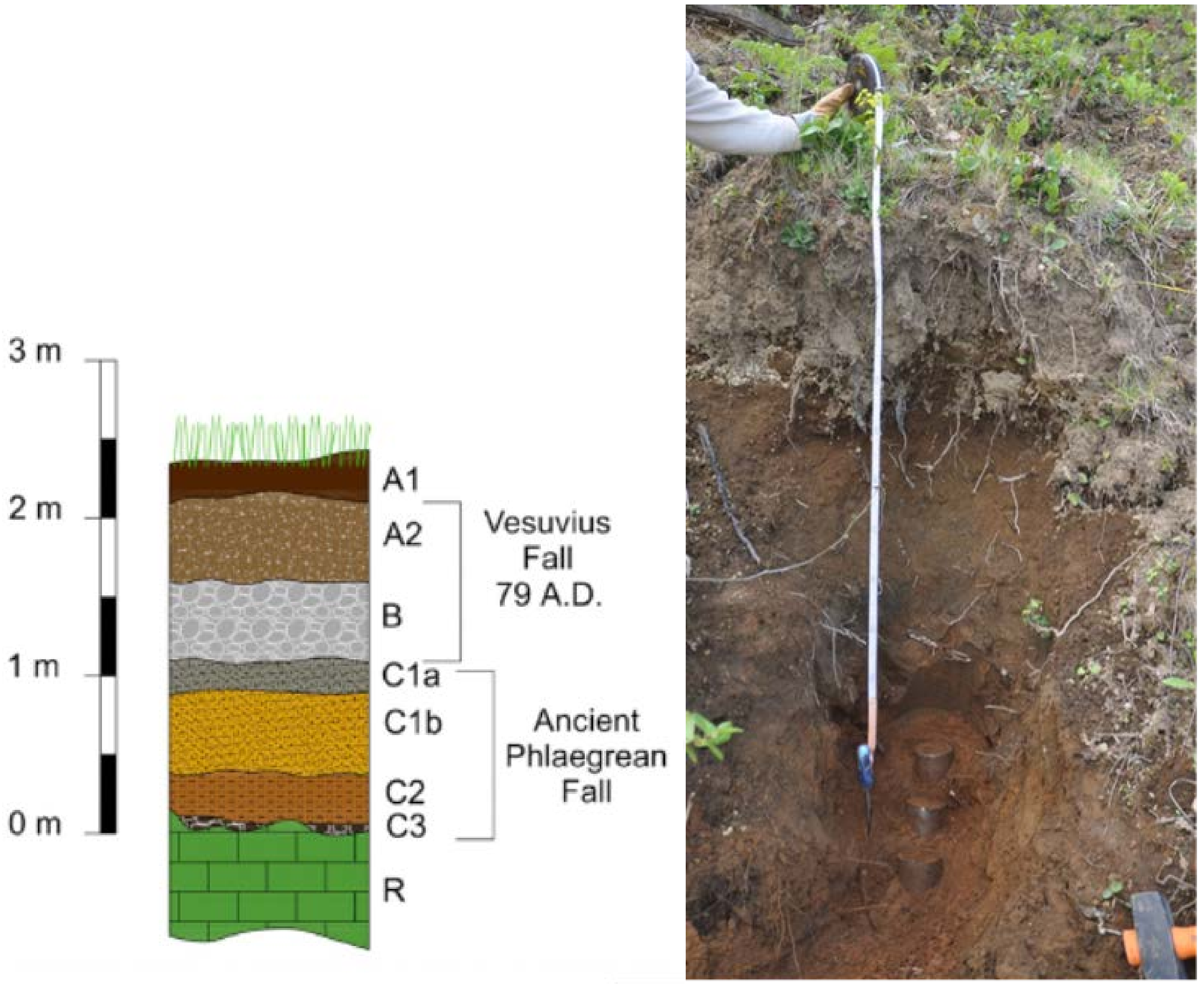

Figure n.161 - Stratigraphic column of pyroclastic deposits of the Monti Lattari on the left; cineritic levels A1, A2 and C sampled on site (right).

From an initial campaign phase, the materials used for the construction of the different samples were collected: grey tuff, pozzolan, lapilli, yellow tuff and fire sand (Figure n.162).

Figure n.162 - Natural materials collected in the Sorrento Peninsula and object of research activity

6.3.3 Geo-mineralogical characterisation

To study the mineralogical composition of crystalline solids, one of the most widely used techniques is X-ray diffraction (XRD). This technique is based on the interaction between matter and electromagnetic radiation of wavelength (λ) in the range 10-2-102 Å. Powder diffraction enables the quantification of the various components that make up a solid sample, through the recognition and semi-quantitative study of the phases, and also allows information to be obtained on the crystal structure and mineralogical composition. The materials in this study were analysed using a Panalytical X'Pert Pro diffractometer, equipped with a PixCel 1D detector, using the Kα radiation of Cu (40 kV, 40 mA) by continuously scanning the diffraction angle 2θ in a range from 5 to 80° (step size 0.0131° 2, 40 s per step). From the analysis of the spectra obtained, it is possible to deduce the predominantly silico-aluminatic nature of the local materials, which suggests their possible use as raw materials for the production of alkali-activated materials and whose mineralogical composition is shown in Table 1. [148]

Mineralogical phase	**Materials**					
	Grey tuff	**Pozzolana**	**Lapillus**	**Grey tuff powder**	**Fire sand**	**Yellow tuff**
Sanidine	x	x		x		
Albite	x				x	
Hematite				x	x	
K-Feldspar				x		
Calcite		x	x			x
Chabazite		x				x
Orthoclase			x			x
Quartz		x			x	x
Leucite					x	
Analcites		x	x		x	
Anorthite			x			
Diopside			x			

Table n.55 - Mineralogical composition of the volcanic materials being researched

6.3.4 Alkali-activated materials

Alkali-activated materials (geopolymers) are inorganic materials resulting from polycondensation processes of silica-aluminate sources in strongly alkaline environments. Consolidation results in products consisting of a three-dimensional Si-Al lattice of SiO_4 and AlO_4 tetrahedral that alternately share oxygen. The empirical formula is:

$$M_{n/z}[-(SiO_2)_m-AlO_2-]_n \cdot wH_2O,$$

where m is equal to 1, 2 or 3, M is a z-valent cation, e.g. Na+, K+ and Ca2+, and n is the degree of polycondensation.

The Si/Al ratio in the lattice is the key parameter for defining the structure and thus the properties and applications of alkaline-activated materials. The success of alkaline activated materials also derives from their versatility, due to the possibility of obtaining different products for different applications, simply by modulating the starting system and some process parameters. They also represent a sustainable alternative to the use of traditional binders. The low environmental impact derives from various factors such as:

- easy availability of raw materials, which can be natural or waste from other industrial processes [149-152];
- simple and energy-sustainable production processes;
- physical-mechanical performance (volumetric stability, mechanical strength, durability, fire resistance and thermal conductivity) superior to traditional building materials (e.g. cements, ceramics, refractories)

Literature shows that a wide range of silica-aluminate minerals can be considered as potential precursors of geopolymeric materials and in particular excellent results are obtained from minerals with a three-dimensional structure, such as zeolites [149]. In addition, any material with pozzolanic activity or a source of reactive silica and alumina, and therefore capable of dissolving easily in alkaline solutions, can act as a geopolymer precursor in a geopolymerisation reaction. These considerations, together with the excellent results obtained from the use of natural and synthetic zeolites as materials with pozzolanic activity [153, 154, 155], lead to foresee interesting potentialities of the materials characterising the territory of the Coast, as alkali activated materials, in the form of mixtures aimed at the recovery and maintenance of dry-stone walls.

The research activity consists of a first phase of characterisation of the raw materials, which includes the evaluation of their reactivity in an alkaline environment, through experimental tests, and the determination of their chemical-mineralogical composition. In particular, the tests for the evaluation of reactivity involve the static and dynamic contact of the powders of the materials analysed with alkaline solutions based on NaOH at different molarities and for different time intervals with the subsequent chemical analysis of the eluate at pre-established times [149]. From the amount of Si and Al released from the powders following exposure to the alkaline environment, it is possible to estimate the reactivity of the raw materials. To support these investigations, the chemical composition of the raw materials is evaluated according to the following procedure: the powders are first calcined at 550°C for 2 h, then a weighed quantity of the dry samples is subjected to digestion, through microwave-induced heating, in a standard solution prepared by mixing 1 ml of HCl (37%, w/w), 1 ml of HNO_3 (65%, w/w) and 4 ml of HF (39.5%, w/w). After the addition of 24 ml of 8 M H_3BO_3 solution to achieve fluorine complexation, the resulting solution is analysed by plasma emission spectroscopy (ICP-OES).

Next step is to optimise the mix design and the process parameters to be selected appropriately for the preparation of the binder mixtures to be used in the dry walls; particular attention should be paid to the evaluation of the activator/binder ratio, the alkalinity of the activator solution, the curing time and temperature.

The final phase of the experiment involves characterising the chemical-physical and mechanical properties, durability and resistance to aggressive environments of the binder mixtures produced. After verifying the actual presence of geopolymer phases by means of infrared spectroscopy (FT-IR) analysis, the actual density, apparent density and porosity of the various mixtures are evaluated by means of water absorption tests. In particular, these tests involve a preliminary phase of drying the samples at 60°C until they reach a constant mass, i.e. until the difference between two successive weights, at an interval of 24 hours, is less than or equal to 0.1% of the mass of the sample. Once the constant mass regime has been reached, the samples are placed, until they return to room temperature, in a silica gel desiccator, which prevents the samples from absorbing moisture again. Once the dry weight of the samples has been assessed (M_1), they are placed in a further glass chamber in which the pressure is gradually reduced to a value close to 2,667 Pa and maintained at this level for 24 hours, to eliminate the air in the pores of the samples.

Then, again under vacuum, water is introduced into the glass chamber and the samples remain immersed for another 24 hours. Finally, the samples remain immersed in water at atmospheric pressure for another 24 hours. After these operations, the samples are weighed with a hydrostatic balance (M_2) and, dried quickly with a damp cloth in order to remove only the surface water, are weighed saturated with water (M_3). By processing the three weights M_1, M_2 and M_3, it is possible to calculate the porosity accessible to water, the apparent density, the real density and the water absorption. Subsequently, the mechanical characterisation involves the fabrication of standard prismatic specimens (40x40x160 mm^3) for the determination of flexural and compressive strengths.

Durability and resistance to aggressive environments is determined by prolonged exposure of the binder mixtures produced to highly aggressive and highly concentrated chemical solutions (mainly chlorides, sulphates and acids of various kinds) and subsequent evaluation of their behaviour by comparing them both with the untreated binder mixtures and with standard samples of Portland cement to be used as reference.

Finally, particular attention will have to be paid to the detailed study of the compatibility of these alkali-activated mixtures with pre-existing materials in order to assess the feasibility of their use and the effectiveness of any restoration work.

A summary of the planned research activities is schematically shown in Figure 163. [148]

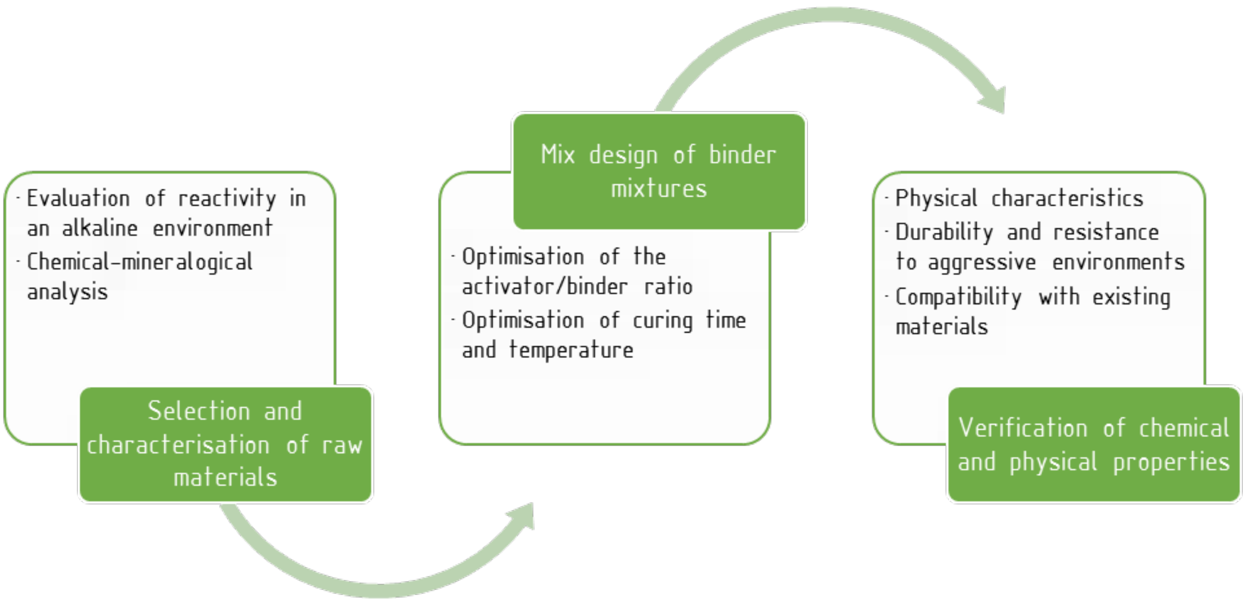

Figure n.163 - Graphical representation and summary of the planned research activities

6.3.5 Potential applications

The use of local volcanic and sedimentary materials in construction has been found as early as Roman times when, mixed with lime, they were used as aggregates. Samples taken by Rispoli Concetta in 2016 [156] reveal the presence of materials belonging to the eruptive products of Somma-Vesuvius, including durece, while in 2019 the use of aggregates and reactive aggregates in a calcitic binder was confirmed in ancient mortars, which were in use until the end of the 19th century when Portland cement appeared [10]. Moreover, as the above-mentioned researcher recalls, the treatise "De Architectura" by Marcus Vitruvius Pollio (80-15 BC), dedicated to the emperor Augustus, described the combination of lime with volcanic deposits to confer hydraulic properties and improve mechanical resistance, without forgetting the reuse of residual materials from construction that today we would identify with construction and demolition waste, such as ceramics, bricks, blocks and cocciopesto [157].

This practice, combined with the technical knowledge of the art of dry stone walling, could lead to an innovative response to the problem of maintenance and consolidation of dry stone walls through injections based on environmentally friendly materials, moving away from the use of materials that are completely foreign to the nature of terracing.

The cultural and technological value is also and above all determined by the interaction that man's works have with the landscape and the natural environment in which they are inserted and of which they are part. Such an exceptional example of traditional building culture and technique as that of the terraces in the UNESCO cultural landscape of the Amalfi Coast, but also in the neighbouring areas of the Sorrentine peninsula, the Phlegrean islands and Capri, cannot disregard the use of local resources.

The contribution that this line of research wants to give, in response to the problem of hydrogeological risk and the growing interest in these artefacts, also underlined by the recent National Plan for Recovery and Resilience (PNRR) of the government, is mainly of an operational nature for the actions of protection and maintenance of the dry stone walls produced by a wise millenary Mediterranean culture. This first phase of the research work saw the selection and analysis of local loose materials, from which good reactivity values in an alkaline environment emerged; these results lead us to consider the production of alkali-activated binder mixtures to be used, by virtue of their high eco-compatibility, in place of other materials, such as concrete, which is poorly adapted to the peculiarities of the sites, for the production of reinforcing mortars, injections and for the restoration or construction of new rubble.

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CHAPTER 7. Conclusions

This research is the result of interdisciplinary work in the scientific fields of technical architecture and the science and technology of materials, starting with a problem of interest in the building industry. The strong belief in the complementarity of this area of knowledge, together with the experience of professional practice in the field of construction and demolition, has led to the investigation of the technical and technological possibilities of reusing materials from construction and demolition activities, with the aim of reintroducing them into the construction market.

Considering the practical and applicative purpose of the project, this interdisciplinary approach proved to be, without too much surprise, extremely appropriate and highly decisive, especially in the overall international approach made possible by the joint supervision of the Universities of Naples and Madrid.

The main objective was the development of new sustainable construction materials with a geopolymeric basis using demolition waste through a comprehensive survey of previous applications. Following the selection of construction and demolition residues, their geopolymerisation capacity, chemical and physical characterisation, and mechanical properties were analysed in order to propose applications in the construction field.

The selection of materials was made taking into account those materials produced in the largest quantities, in consideration of the environmental impact that these percentages have 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 Madrilenian areas and in the construction sector in general were analysed, produced and tested respectively: tuff, brick and cement. From these demolition residues, forty-five prismatic samples, forty-nine cubic and cylindrical specimens and six sample tiles were made in the laboratory.

Chemical, physical and mechanical resistance characterisation tests were carried out at the TEMA Lab of the Escuela Técnica Superior de Edificacion of the Universidad Politécnica de Madrid and at the materials laboratory of the DICMaPI - Department of Chemical Engineering of Materials and Industrial Production of the University of Naples "Federico II".

From the results obtained, it emerged that there is enormous potential for reusing the raw materials used in the production of geopolymer-based construction materials. In particular, it was found that the materials produced on the basis of cement give considerable results from a chemical point of view for geopolymerisation and appreciable results from a mechanical point of view, for this reason it is believed that further in-depth studies on the mixtures also with the addition of other types of waste construction materials that improve their mechanical performance, may lead to appreciable results; the materials produced from tuff have some difficulty in geopolymerising at high concentrations, however it is possible that the development of a different mixture will give good prospects for use especially in applications that require compulsory compatibility with the tuffaceous material making up the buildings. The materials produced from bricks give optimal results from a geopolymerisation and performance point of view; however, given the potential of the mixture, it is equally interesting to investigate other possible applications together with the development of different types of mixtures to evaluate and compare their performance.

The growing interest in the recovery of materials from construction and demolition activities is increasingly directed towards innovative and sustainable reuse. As studies have shown, the final phase of a building's life cycle, which is the most wasteful from an environmental point of view, can be transformed into an opportunity to optimise the consumption of primary resources, thus ensuring that attention is paid to environmental issues that are no longer negligible. Although there is still a long way to go before raw materials can be completely reintroduced into the production cycle, it is essential to pursue this goal by carrying out experiments and collaborations to raise awareness among the main players in the industrial production process of building materials. In fact, the decision to use secondary raw materials, deriving from construction and demolition activities, in the production process of sustainable materials to be reintroduced into the construction market, represents an intelligent and ecological solution to the significant environmental problem of disposing of this type of widely available waste. The applications researched have therefore taken into account the possibility of recovering the greatest quantity of waste material through solutions that can be used both in the field of new construction and in the field of rehabilitating the built heritage thanks to the chemical-mineralogical compatibility of geopolymers.

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Acronyms and Abbreviations

TV - Viterbo Tuff

TGN - Yellow Neapolitan Tuff

SS - Sodium silicate

NaOH - Sodium hydroxide

CDW - Construction and Demolition Waste

C - Cement (waste material)

CP - Cocciopesto (waste material)

M - Mixed tuff, brick and cement (waste material)

T - Tuff (waste material)

R - Weight ratio