The recycling of crushed waste bricks in the self-compacting mortar

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THE RECYCLING OF CRUSHED WASTE BRICKS IN THE SELF-COMPACTING MORTAR

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ABSTRACT

One of the most challenging tasks that humankind has in the future is to develop new cities for a growing population in spaces and with materials that are not as abundant as in the past. In order to face this difficulty, buildings should be designed and constructed with cutting-edge technologies that aim to reduce their impact on the environment. The use of virgin raw materials in the building phase is still the most convenient solution in terms of organization and economic budget, but it worsens the exploitation of quarries in the territories.

Moreover, the disposition of old and abandoned buildings all over the world, is another unsolved issue to be addressed by the building industry. Their demolition is often preferred due to simpler procedures and a quicker creation of a possible available spaces for other purposes, but leads to another tricky problems, that of managing the wastes generated. To avoid the frequent disposal of inert material in landfilling, the European Community enacted the Directive 2008/98/CE that sets the objective for each state member to achieve by 2020 a minimum of 70% by weight of re-use, recycling and recovery of non-hazardous construction and demolition wastes.

The aim of this study is to analyze the possible recycling of waste bricks coming from demolition for the production of self-compacting mortar (SCM). The investigation is performed on mortars made with different replacement's percentage of the limestone filler, in one case, and of the limestone sand, in the other. First, the bricks are prepared and treated to achieve the similar physical properties of the filler and the sand of limestone. Then the materials are characterized in order to make a comparison with the limestone fractions and to design the mix for the mortar. Several tests are performed to highlight the influence of the recycled material in the traditional mix of the mortar. The analysis is done on mortars' samples through the concrete equivalent mortar (CEM). Moreover, for this specific case study, it is avoided the traditional use of the superplasticizers, in order to enhance the behavior of the bricks fraction and its influence on the mortar. Finally, the study of the compressive strength and flexural strength demonstrates how the substitution can affect or improve the mechanical properties of the hard mortar samples.

The study demonstrated that the use waste bricks' fractions to substitute sand and filler fractions inside self-compacting mortar is possible. The water absorption of the recycled material plays a fundamental role in designing the proper mortar's mix. Several parameters must be considered during the choice of the composition, especially the amount of water to add and granulometry. In the case of the limestone filler replacement by the bricks' filler, the workability is only partially affected. Moreover, the mechanical properties of the mortars present negligible changes compared to the reference mortar. Sand replacement with bricks sand, does not reduce significantly the workability of the mortars, even with further increases of the bricks sand content. The small differences in compressive and flexural strength between the reference mix and the new samples, demonstrate that the brick's sand does not change significantly the final mechanical properties.

Keywords: *Construction and Demolition wastes; Self-Compacting Mortar (SCM); recycling in mortar; recycling wasted bricks*

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Introduction

Over 850 million tons of wastes coming from the construction and demolition sector are produced every year by the European community, representing the main and significant stream for the waste generated by the state members [1]. This fraction contributed for the 34.7 % of the total amount of waste produced by the EU-28, according to the Eurostat statistics of 2014, with an average production of 1.7 tons per inhabitant per year [2]. Due to the constant growth of the world population, the resulting increase in the construction of the building showed no sign of diminishing. Moreover, the construction industry is also responsible for the exploitation of a huge amount of raw materials together with the production of a considerable volume of wastes in several steps of the construction phase. In particular, the main processes with the greater impact are the extraction of raw materials, the manufacture of new products, the backfilling by the materials and the demolition, which is the topic more current [3].

This sector doesn't represent only the main industry for the usage of natural resources, but also the main voice for the consumption of energy (40% of the world consumption) and the linked emission of CO_2 [4]. The research of new areas to produce raw materials and for the backfilling of the Construction and Demolition waste (C&DW) can lead to the occupation, in some cases, of potential zones exploitable for other purposes. So, in the European context, to face the possible future environmental and social difficulties, resulting from these actions, was enacted in the 19th November 2008 the European Directive 2008/98/CE [5]. One of the objectives for the state members, specified in this document, is the achievement of 70%, minimum, in weight for the re-use, recycling and recovery of the non-hazardous construction and demolition wastes by 2020. Certainly, the construction sector, with the passing of the years and the regulations issued, is becoming more aware of the importance of the by-products' retreatment inside its processes. Several types of research have investigated the addition of different materials, the majority with the same nature as the common C&DW, in the manufacture of the most common product for the building industry: the concrete. Since the environmental issue has become increasingly urgent, several studies have been carried out to investigate the reuse of particular materials, which, in some cases, may represent a common refusal deriving from the construction and demolition of buildings. The choice to recycle a substance in the concrete production process, for example, can represent not only an advantage in terms of environmental impact but also in economic terms, leading to saving materials whose cost may also affect the construction budget.

In this work, the re-use of bricks inside the mixture for the production of a self-compacting mortar is carried out, analyzing all the aspects related to the characterization of the material and comparing the results to a traditional reference mix.

The main objective is to study the influence of bricks on the mix for the self-compacting mortar in terms of behavior and properties both for the fresh and the hard state. The investigation is performed on the substitution of two main fractions which are traditionally present inside the SCC mix: the limestone filler and the limestone sand. Different percentages of substitution are analyzed to highlight the variations in the properties of the mixture.

First, the general situation of the C&DW management is presented for what concern the European context. The classification and the main properties of this kind of waste are described. Then, the main principles for the recycling of the C&DW are explained. Moreover, the researches about the recycling of this kind of wastes inside the production of the Self-Compacting Concrete (SCC), first, and, secondly, in the Self-Compacting Mortar (SCM) are described. Then, the Self-Compacting Concrete (SCC) is presented with its main features and properties.

Subsequently, the preparation of the bricks samples is showed in all the steps. The treatments are described in detail in order to present all the conditions and parameters, which could play an important role in the final results. Thanks to this description it is possible to comprehend better the results coming from this study and the role of the treatments performed on the bricks.

After, the methodologies and the characterization tests of this work are described to clarify all the analysis performed. Each test carried out is explained in its procedure and objective.

Then, the work is divided into two different parts. The characterization results are presented for the two kinds of material produced during the treatments on the bricks: the sand and the filler samples. The results are then compared with the ones obtained for the limestone filler and the limestone sand to understand the possible differences and try to forecast the following behavior of the mortars produced. The characterization's results are also described for the other constituents present inside the mixture for the SCC, in order to underline and clarify the fractions used for this case study.

In the last part, the investigation on the mortars is conducted both for the fresh and hard state. In one hand, the rheological and the fresh properties of the mixture are compared in the analysis of several compositions, made with a gradual replacement of the limestone fractions by the bricks samples. On the other hand, the mechanical properties of the mixes are evaluated through the measurement of the compressive and flexural strengths, which are considered as the main parameters for the design and the construction phase of a building.

Finally, after the discussion of the results obtained, the conclusions sum up all the aspects recorded from the different steps to argue feasibility of the bricks' application inside the SCM.

1. Construction and Demolition Waste (C&DW)

Generally, the demolition of buildings creates large quantities of wastes to which those coming from the construction of new ones are added. Demolition, nowadays, is fundamental for the improvements of small and big cities, where the main problem is represented by lack of spaces. In other cases, demolition can be chosen in order to extend the building's lifespan or, for specific situations, for their rehabilitation and renovation.

There are several ways to define the wastes coming from construction and demolition of buildings and they depend on the regulations of the country where they are produced. In some case, a specific category of wastes, as from infrastructure and roadworks together with the excavated soil, are not even included inside the definition of construction and demolition waste (C&DW). In the US, the Environmental Protection Agency (EPA)defines this kind of material as "waste that is generated from the construction, renovation, repair and demolition of structures such as residential and commercial buildings, roads and bridges" [6]. According to the European Community and to the European protocol management of September 2016, C&DW is defined as "any waste generated in the activities of companies belonging to the construction sector and included in the category 17 of the European List of Waste" [7]. Moreover, both the classifications include also the excavated soils from contaminated sites, which are usually not considered as strictly linked to the construction industry. Further classifications of the wastes coming from the construction and the demolition are available. Tchobanoglous et al., in 1977, divided this kind of by-products through the following definition: "wastes from razed buildings and other structures are classified as demolition wastes. Wastes from construction, remodeling and repairing of individual residences, commercial buildings and other structure are classified as construction wastes" [8].

The generation of construction wastes occurs mainly in four processes of the work site: the design, the procurement of materials, the management of the remaining resources [9]. On the other hand, the demolition wastes present a higher heterogeneity, compared to those coming from construction, since they are made mostly of materials frequently contaminated by elements potentially hazardous for the environment (paints, adhesives and coverings). Furthermore, the composition and the distribution of materials inside the demolition waste depends mainly on the typology and the lifetime of the structure. The materials used for the construction of the building cover a significant role in the final composition of the wastes. For these reasons, the management of the C&DW cannot be simplified in one generic solution but has to be adapted to each different condition.

Currently, demolition represents the best option for the treatment of buildings, because it offers more advantages from the economic point of view and from the time-consuming aspect. The demolition and the construction are not the only sources of wastes. These sources generate not only wastes but also a significant number of complications. Indeed, transport and processing to the landfill are challenging activities. The increase of urbanization, with the related development of constructions, during the last decade of the 21st century, increased the stream of wastes sent to landfills, being this the simplest solution [10]. Thanks to its chemical nature, C&DW can be handled in this way without causing remarkable environmental problems. Moreover, this option represents the most suitable because the usual treatments performed on wastes (aerobic and anaerobic digestion, thermochemical digestion, incineration and composting) are not effective on the C&DW [11].

The construction industry has remarkable environmental impacts on each activity, starting from extraction of raw materials, to production, processing, transportation and final construction, until demolition, Indeed, through a deep analysis of the sector, it can be finally defined as a wasteful sector from the exploitation of natural resources to the general production of wastes and the emission of pollutants in the environment [12]. It represents the first sector for the use of raw materials, with three thousand billion tons per year worldwide, a role that cannot be approached in a traditional way.

The heterogeneity of the construction and demolition activities does not allow a reliable analysis of consumption of construction materials nor the production of demolition wastes per capita. Using precast or prefabricated structures permits a lower production of wastes compared to the traditional process Generally, the composition of C&DW can be summarized in the following Table 1.

Waste category	min. range (%)	max. range (%)
Concrete and Masonry	40	84
Concrete	12	40
Masonry	8	54
Asphalt	4	26
Others (Mineral)	2	9
Wood	2	4
Metal	0.2	4
Gypsum	0.2	0.4
Plastics	0.1	2

Table 1: The Composition of C&DW [13].

1.1 Classification

The elements, which compose the C&DW, are not always constant, but they depend on several aspects: the technique used for the construction, the type of structure and the economic and social situation of the country. However, as mentioned before, the wastes can be categorized according to their origin, as *Fatta et al.* proposed in their research [14]:

1. By demolitions: materials and debris composed mainly of soil, concrete, bricks, sand, rocks and gravel. Generally, their composition can differ depending on the location, the shape, the age and the purpose of the building.
2. By the worksite: materials produced by the employers during the operations on site, which are mainly represented by wood, plastic, paper, glass and metal;
3. By excavations: the excavated soil, the vegetation and the rocks coming from the foundation's works and the leveling of the work site composes usually this type of wastes;
4. By road maintenance works: the main materials are the asphalt with the sand and gravel coming from the road’s pavement;

However, the major production of the C&DW is present in the construction, the renovation or the demolition of buildings [10]. In the 1999 European context, the partitioning of these categories reached the percentages displayed in Figure 1.

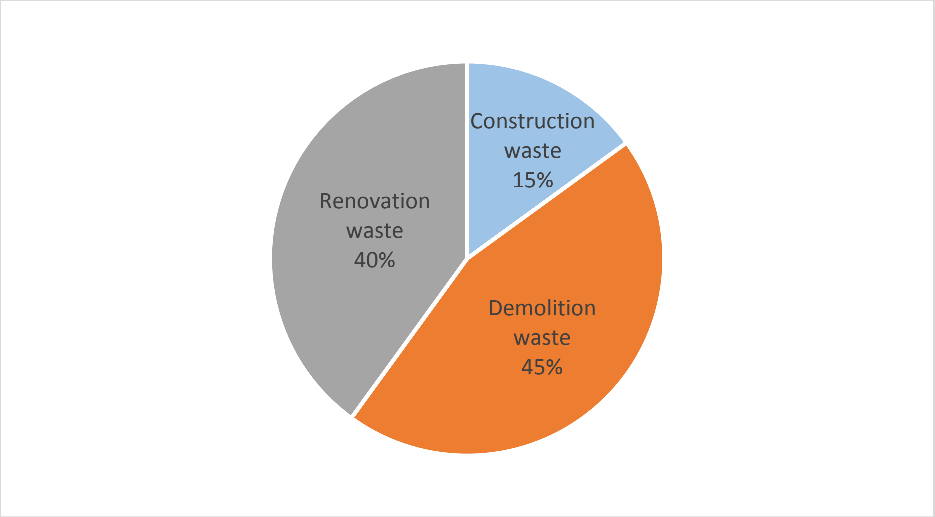


Figure 1: Division of the C&DW related to the building sector [15].

Already in 1974, one of the first classifications on the C&DW waste was proposed by Spivey [16]. The categories were created to relate the wastes to their sources, as follow [10]:

- Demolition waste (concrete, bricks, tiles etc.);
- Packaging wastes (paper, plastics, cardboard etc.);
- Wood waste;
- Concrete;
- Asphalt;
- Sanitary waste;
- Metal waste;
- Rubber;
- Glass;
- Pesticides and non-pesticides containers;

According to the European Waste Catalogue (EWC), the member state of the European community is encouraged to respect the classification for the management and the collection. Each material is categorized through a code to allow a better identification and simplify the sorting of these materials. The classification of the wastes is the following one.

- Concrete, bricks, tiles, ceramics and gypsum-based materials (code 17 01 00);
- Wood (code 17 02 01);
- Glass (code 17 02 02);
- Plastic (code 17 02 03);
- Asphalt, tar and tarred products (code 17 03 00);
- Metals (code 17 04 00);
- Soil and dredged soil (code 17 05 00);
- Insulation materials (code 17 06 00);
- Mixed construction and demolition wastes (code 17 07 00);

As seen, the classification of the C&DW can be carried out with different principles and rules. Nowadays, the majority of the European state members use the classification given by the EWC, referring to the nature of the material and to the code given for each category.

The classification according to the source and the origin may lead to advantages, revealing enough information about the wastes nature. This aspect can be useful to distinguish between the demolition wastes, in which it's easily the cross-contamination with other materials, and the excavated soil where, basically, the material is homogenous.

1.2 European context

Since the circular economy started to cover a more important position in the society of the 21st century, the European Commission, on December 2015, proposed new regulations and standards to promote it. The waste management and its legislation depend on the European laws. The European legislation, with its regulations and principles, bound all the member states of the community and the ones inside the European Economic Area (EEA).

The approach to the waste management by the European community showed two different approaches before and after 1990. Between 1975 and 1990, the European legislation about wastes was based on the administrative requirement. The states were obliged to propose a waste management plan and to transpose the European Waste Catalogue (EWC) [17] established by the European Community. In the years before 1990, there were no obligations on the treatment method of the wastes by the member states. After 1990, several regulations and targets on the recycling of the wastes were presented by the introduction of new directives.

Moreover, the new proposals and the modification of the European Directives led to some variations for the usual waste management in each state [18]. The proposals were sent to the European Council and Parliament to be approved, leading to the creation of new six directives. Among these, there were also present: The Waste Framework Directive (2008/98/EC), the Directive linked to the landfills (1999/31/EC) and to the electrical waste and electronic equipment (2012/19/EU).

The main objectives [19] of the new proposals in the directive were:

- Reaching the recycling of the municipal waste of 60% by 2025 and of 65% by 2030;
- Recycling the 65% of the waste produced in the packaging by 2025 and the 70% by 2030;
- Prohibition of landfills with wastes coming from separation processes;
- Improve the collaboration between the state members on the management of the wastes;
- Simplify the definitions and the terms linked to the wastes;
- Create a common method for the computations of the recycling rates;
- Design a criterion for the responsibility of the producers;

In Europe, about 850 million tons of C&DW are produced every year representing the 35 % of the waste total quantity [2]. In 2008, the European Council together with the Parliament reached an agreement on the recycling of this kind of wastes. The regulations on them are contained inside the Waste Framework Directive 2008/98/EC [18]. It regulates the general terms of the waste legislation, concentrating the attention on the management measures and the obligations for the originators and the owners of wastes.

The directive for the C&DW management declares the next target for the member state: "By 2020 the preparing for the re-use, recycling and recovery of non-hazardous construction and demolition wastes excluding waste defined in the category 17 05 04 in the European Waste Catalogue (EWC) shall be increased at least of 70% by weight".

Due to the different context between the states members of the European Community, the production and the management approach of the CDW cannot be similar.

In 2012, the generation of C&DW in France reached 246 million tons, representing the highest case of all the European Community. Although the presence of this large amount of wastes coming from buildings and demolitions, the index linked to their recycling, equal to 45% of the total up to 2011, is lower than the European average which is equal to 55% of the total [20].

On the other hand, Germany, even if with a similar amount of wastes produced, has higher recycling and recovery rates compared France. Indeed, with an annual production of 200 million tons, the recovery rate is over 80% [21]. *Nelles et al.* estimated the total yield, by the efficiency and the management of the wastes, to approximately 40 billion euros with a linked employment of about 200,000 people [22].

In 2012, the production of the construction and demolition wastes by Italy recorded an annual value of 40 million tons. The recycling rate reached 75 % of the total production, overcome the average trend of the European community of 55% [21].

Austria, through its 2358 administrative units along the country, represents one of the most advanced countries in the management and the recycling of wastes, with the highest rate of all the Europe [21]. In 2013, around 35 million tons of C&DW were generated, including the excavated soils produced during the constructions works [21]. Between 2004 and 2006, the C&DW recycling rate reached 60%. While in 2013, Austria had already recycled 87% of the C&DW produced annually.

In 2015, Spain produced around 30 million tons of C&DW, which represents one-third of its total waste production. The composition of the C&DW is mainly characterized by bricks, tiles and ceramic-based materials with 54 % of the total amount. The concrete, secondary, represents the 12% [23].

The annual production of C&DW in Sweden is generally lower respect to the other countries, with a value of 8 million tons of waste (2014) [24]. Although the amount of waste is not so large, the recycling rate of Sweden, with a value of 50%, is still under the European average (55%).

In the Czech Republic, the C&DW are composed in the majority by soils and excavated materials. However, the concrete fraction started to show an increase trend in the earlier years. Until 2012, the production of C&DW overcame 13 million tons per year[25]. Nowadays, the wastes coming from the construction and demolitions represent 46 % of the total production. Huge improvements were reached during the last years, leading to a recycling rate of 95%. This process started in 1996, with interesting results after a few years, until 2005 when the recycling capacity of the country doubled the required operating capacity [26].

The Netherlands represented, more than ten years ago, one of the main states for the demand of raw materials with 150 million tons per year [24]. In 2012, the production of C&DW, however, was around 81 million tons, covering the 40% of the total production. Then, in 2013, the recycling rate reached 80% of the total amount and 10% of wastes used for the energy recovery by incineration [27].

In Denmark, the concrete fraction represents the major part of the C&DW, with an annual production of 5 million tons. From 1997 to 2013, Denmark has doubled the production of C&DW per year, increasing together the recycling rate. Unlike the usual choices, the aim of the state is to invest in the recycling of C&DW through new roads construction with innovative materials [28].

According to 2015 statistics, Estonia produces nearly 2 million tons of C&DW with a recycling rate of 95 %. It was one of the firsts countries, together with Germany, Denmark, Ireland and Netherland, to achieve the target of the recycling rate for this kind of waste imposed by the European Community [29].However, this kind of waste represents a small fraction of the total annual waste production (8.8%).

This trend indicates the lower growth of the construction industry compared to the other European state members.

In 2012, the UK production of the wastes reached 200 million tons, with the majority coming from England (81%). The half of the total production consisted of wastes from the construction and demolitions activities, of which 85% were produced by England. Between 2000 and 2008, the recycling rate of 49% represented a lower value compared to the European average [30]. Nowadays, after important investments in this sector, UK has already reached the target of 70% of recycling rate by 2020 imposed by the European Directive. Indeed, it reached the 86% of recycling both in 2011 and 2012 [31].

As shown by the examples in Europe, the trend of the C&DW production is increasing uniformly. Although there are several differences between the countries, the recycling represents the most suitable way to treat this kind of materials. It can produce, in certain conditions, improvements both for the economic and environmental aspects. In the end, the potential of the recycling depends mainly on the developments of the most appropriate ways to manage the materials and on the study of innovative techniques to reach satisfactory qualities.

1.3 Recycling of C&DW

Depending on their territory and their environmental characteristics, some countries have a low concentration of the main raw materials used in the construction sector. This aspect led, in the 70s, to the development of techniques of C&DW recycling. In the 80s, due to the reduction of available landfills and because the general concern on pollution, recycling of C&DW started to be exploited through the construction of the firsts recycling plants. This trend was boosted also by the transposition of the European Directive 2008/98/EC [32].

C&DW recycling leads to several benefits in social, environmental and economic terms. The re-use of this type of wastes guarantees the reduction of the areas exploitation together with the decrease of the natural resource consumption. This improves the environmental impact of the building, due to the utilization of materials that otherwise would be sent to landfills.

Usually, after the generation of the C&DW, the material produced is considered as a homogeneous waste coming from the process. This method, however, does not allow the appropriate valuation, losing the real opportunities that this type of resources offer if they are treated in the proper way. The separation and the concentration of the several materials inside the C&DW cover the main step for the valorization of this type of wastes [33].

According to the circular economy point of view, the most appropriate way to re-use in the construction sector is the recovery of the building without any demolition. However, the aspect such as space, the costs and the client opinion have some influence on the feasibility assessment of the building re-use. Usually, for this reason, the simplest and more employed option is the demolition. This lead to a large production of wastes, which in the end counts for a significant portion of the total stream. To avoid this result, the selective deconstruction is in some cases taken into consideration. It consists of the disassembly of the building to re-use and recycle as much material as possible from the materials that composed the structure.

The deconstruction starts with the evaluation and the removal of the hazardous material still present on the structure. Then, the dismantling of the direct re-usable material, as glass, wood, radiators, heating boilers is performed. When the building can be considered as empty, the coverings of the floor and ceilings together with combustible and non-combustible materials are removed. In the end, if they are present in the building, the wooden beams and the steel frame are recovered. Otherwise, if the building is made of concrete, the structure is demolished to produce concrete waste aggregates which can be re-employed inside the concrete production. The main advantages with this type of approach are the increase of recoverable materials and a more sustainable re-use of the wastes. Despite being the best way to obtain several materials from a building, this method is not chosen so often. Indeed, the longer periods involved in selective building deconstruction, together with the economic costs, are usually higher compared to the traditional demolition expenditures.

The demolition, on the other hand, represents the simplest and less time-consuming solution, if well projected, for the constructions treatment at the lifetime end of the building. However, in this way, the materials with different natures are mixed in the composition of the final C&DW. So, the quality of the mix decreases due to the contamination of several materials. Indeed, the quality of the waste is one of the features which can be modified more easily during the demolition.

The cross-contamination is a possibility which can happen during the demolition itself, the collection, the separation and the storage of the material. The most usual contamination during the demolition process is that of asbestos. To avoid it, the first control on the material is performed through visual inspection directly on the work site. Traditionally, the use of materials needed for the construction industry is based on a linear process, from the extraction to the utilization, in which the destination is the disposal and the storage of the material (Figure 2). The linear approach leads to the production of valuable wastes coming both from the construction and demolition, which will end up in the landfills creating a considerable environmental impact.

Figure 2: Traditional linear management of the resources [34].

Nevertheless, in the last few years the traditional method for the construction materials changed from a linear production of the resources to a circular approach for the manufacturing activities (Figure 3).

The choice of this new methodology leads to changes in the products and materials design, to maintain, during their lifetime, their main properties. Indeed, at the end of their life cycle, the waste can be re-employed through the substitution of the raw materials, becoming a resource for another process. The concept at the base of the circular approach is the cradle-to-cradle with the production of zero wastes from the construction and demolition sector [34].

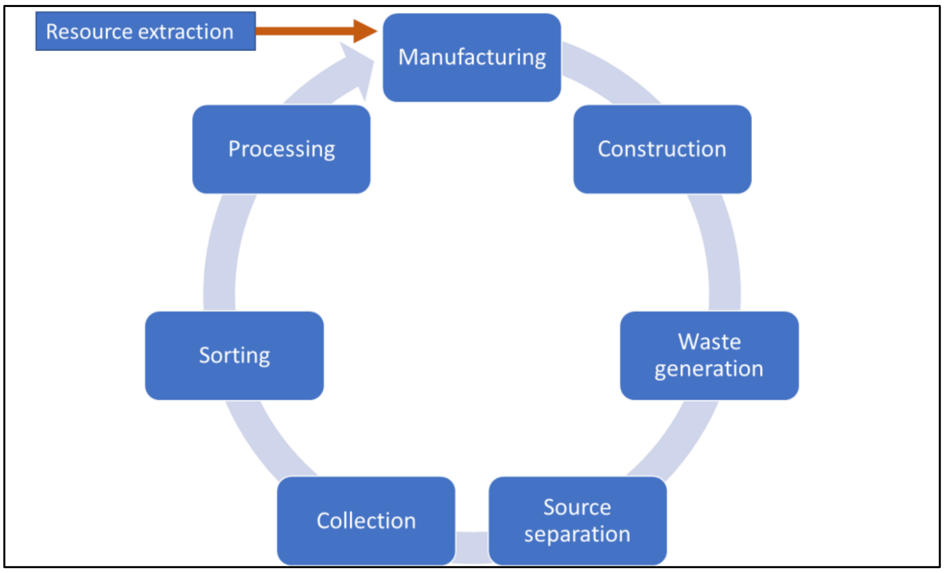


Figure 3: Circular approach to the resource for the construction sector [34].

The concept is to collect the materials from the buildings, before and after their demolition, to reintegrate them in the construction sector or in other industries where their properties can be exploited, without creating further wastes. Although the circular management of building waste is more organizational-intensive, it can be a viable alternative to improve the traditional practices of the sector, thereby lowering its environmental impact.

Generally, the management of the C&DW starts with the removal from the work site to a disposal area or to a recycling plant. Usually, the re-use of material already presents on site is not so common due to the loss of properties during the removal of the materials or the demolition of the building. Currently, the processes and the techniques for the recycling of the C&DW are common and well established around Europe. However, the final products and the relation to the market depends on the rules applied in the country in which the recycling takes place. Usually, the operations of a recycling plant consist of the following steps:

1. Reception with the weighting and the inspection of the materials;
2. Preselection with the rejection and the diversion of undesired materials;
3. Inspection of large objects;
4. Magnetic separation of the metallic fractions;
5. Separation of plastics, wood and other undesired materials;
6. Crushing and grinding of the wastes;
7. Screening and the possible secondary crushing.

The main purpose of the recycling plant is to produce, through the treatment and the processing of the C&DW, inert aggregates. While, the materials such as metals, plastics and woods are sent to more appropriate plants where they can be treated in the most suitable way. The aggregates produced by the plant can be employed to substitute the virgin materials. The main purposes, with the main substitution rate, is achieved for the low-grade application like the foundations and the base of roads and backfilling. In some cases, the material can be upgraded to the recycling, as aggregate, in the production of structural and non-structural objects. However, in the choice of the recycling, the application of standards imposed by the European Union and by the nation itself must be taken into consideration [35].

Although the recycled aggregates, coming from the crushing of the wastes, could appear more environmental friendly and more convenient, in certain conditions they have some constraints [35]:

- The work site can influence both the transport distance, modifying the costs, and the composition, affecting the nature and the final application of the aggregates;
- In the recycling phase, the leachability of the aggregates is not regulated by a fixed standard;
- In the choice of the natural aggregates to be replaced, the life cycle performance of the material is influenced by the purpose, the type and the origin of the virgin resource;
- In some cases, the crushing and the production of recycled aggregates could be more energy intensive compared to the production of raw materials and it becomes interesting only if transport distance is short;

The heterogeneity of the C&DW represents the main challenge during the recycling, standardization and regulation of this kind of materials. The differences in the countries' practices and in the types of projects, depending on the location and design, do not allow a general standardization of the C&DW composition. However, it is possible to predict the largest part of the key components generally present in this waste stream:

- Concrete;
- Masonry (bricks and mortar);
- Ceramics tiles;
- Glass;
- Plastics;
- Metallic material (Steel, Copper and Aluminum);
- Wood;
- Insulation materials;
- Filling materials;
- Paper and cardboard;
- Granite and marble;

These components have already been studied by several researchers through different techniques. The concrete, which represents the main products in the C&DW, can be recycled, after being transformed in aggregates, in the production of new structural material substituting up to a certain percentage the natural aggregates [36]. The same destination might be decided for the masonry fraction made principally by bricks and mortar, which can be a suitable replacement for natural aggregates. Wood coming from particular constructions can be recycled as compost material or for the creation of pulp and paper products. [8].

Elgizawy et al. proposed, basing the analysis on the literature's research and their interpretation, a rank for the material usually present in the C&DW, indicating the different grade of difficulty in recycling. The rank in Table 2 is composed by a value between 1 and 5, where the first stands for a material difficult to recycle and 5 as the easiest one.

Material	Rank
Concrete	4
Wood	3
Ferrous metal	5
Non-Ferrous metal	5
Masonry	3
Plastic	3
Glass	4
Ceramic Tiles	4
Mineral wool	2
Drywall	2
Filling material	3
Paper	5
Marble	3

Table 2: Ranking for indicating the ease of recycling for the materials [10].

Paper, ferrous metals, together with non-ferrous metals, are the easiest material for the recycling. They are treated through efficient recycling techniques which guarantee an up-cycling of the wastes leading to the production of material with a similar value. Concrete, glass and ceramic tiles have lower ranks due to difficulties in terms of techniques' efficiency and to higher costs. The masonry together with the marble and the filling materials, due to the high amount of fine particle's fractions, are not yet recyclable in a suitable way. For the gypsum boards and the mineral wool, the techniques for the recycling are not well advanced both for what concerns the cost-effectiveness and the quality of the final material produced.

In the European context, there is still the need to improve the legislation both at national and European level, to implement the regulations and the data until reaching a suitable management of the C&DW. The recycling of C&DW through the zero-waste approach represents a challenge, in terms of research and experimental work, but it can become a benefit for the promotion of the circular economy, based on the closed-loop management. For this reason, the investigations on the recycling are constantly active to replace the most exploited materials in the constructions.

2. Recycling in the concrete production

Ever since the exploitation of natural resources to produce concrete began, the consumption of raw materials has constantly increased without any deceleration. The demand for new buildings, in the second part of last century, has represented the first reason in the extraction of raw materials. In particular, after the Second World War, due to several economic and political reasons, the growth of cities was one of the main factors in the huge demand for raw materials [37]. On the other hand, the presence of large amount of demolished buildings, due to the damages generated by the war, forced to look for some kind of reuse in the industry, avoiding the accumulation of large amount of wastes. This trend has also led to a growing interest in recycling inside the production of concrete, replacing specific fraction without influencing particularly the final product. The investigation started in the middle of the previous century, but in the last decades, the topic has become fundamental to the vision of the most developed countries in the world.

The wastes coming from the demolition of constructions are an opportunity for the recycling of material as replacements for the aggregates fraction. Its feasibility depends mostly on their physical, mineralogical and chemical properties. Due to the heterogeneity of the construction sector of the different countries, their composition can present a great disparity in the physical and chemical characteristics. The treatments of wastes, before the recycling of them, may also influence the parameters, impacting the final product. For this reason, the knowledge of the physical properties is the first step to complete, since the quality of the final product depends exactingly on the features of the CDW [38].

The volumetric mass

The main feature which distinguishes the traditional natural aggregates from the recycled ones is the density. Indeed, even after some treatments on the recycled aggregates, it is usual to detect some old mortar still attached to the grains. This leads to a decrease of the density and an increase in the water retention, caused by the greater water absorption. If, on one hand, the fine natural aggregates, commonly river sand, presents a volumetric mass equal to 2.65 g/cm^3, the recycled fine aggregates, which usually are coming from the recycling of concrete due to the common presence in the CDW, shows a value 10-15% lower [39].

With recycled aggregates from treatments of masonry, the situation changes. Indeed, the clay bricks with the ceramics, one of the largest parts of CDW, have a lower volumetric mass. This leads to a total aggregates density of 20%, much lower compared to the aggregates made by recycled concrete and of 25-30% lower than the natural ones [39]. The lower density of these recycled aggregates can be caused by the higher porosity, compared to the natural aggregates. Moreover, the higher porosity indicates the higher tendency of the material to absorb a larger quantity of water. Indeed, the recycled aggregates coming from the crushing of masonry show a water absorption which is, generally, higher than that of the natural ones [40].

The shape and the size

The shape of the aggregates coming from the CDW has a reasonable influence on the behavior of the particles inside a possible mix [41]. Indeed, depending on the type of aggregates considered for the recycling, the physical features can be modified. The shape and the size of the aggregates are strictly dependent on the treatment process of the material before the recycling phase. Due to the great impact that has the coarse and the fines aggregates on the final concrete, their characteristics are of fundamental importance to reach the required properties. Both the particles size distribution and the shape of the grains influence the fresh properties of the self-compacting concrete, as the workability and the passing ability. On one hand, the more spherical the aggregates grains are the more they avoid the blocking phenomena, thanks to the reduction of internal friction and to the increase of the workability. On the other hand, the crushed aggregates, with an irregular shape, lead to the improvement of strength properties, thanks to the interlocking between the grains [42].

The size of the grains plays the same important role both on the fresh and on the hard properties. Indeed *Shakir et al.* investigated the influence of the grains size on the properties of the self-compacting concrete. The results showed the worsening of the fresh properties with the increase of the aggregates size. While concerning mechanical properties, the samples with the lower size for the aggregates presented an improvement of values [43].

The saturation degree

The saturation phase of the recycled aggregates covers the main role in the modification of the properties of the particles. Moreover, the humidity of the grains can modify the properties of the concrete product, both in the fresh and in the hard state. The slump flow test performed on mortars with dried and saturated fine aggregates can show the differences. In fact, the mortar, made with the dried recycled fines, presents a high spread and a satisfactory workability compared to the one composed by the saturated fine aggregates. The free water available inside the mix allows, together with the high paste volume, a better workability and flowability. In the case of the recycled aggregates, coming from the demolition of the concrete, the water absorption is faster compared to the natural aggregates. *Ferreira et al*. studied the role of the pre-saturation on the recycled coarse aggregates. The concrete mixes made with the pre-saturation method on the aggregates showed worse mechanical and fresh properties results, compared to the mixes made with the water compensation method [44]. Regarding the masonry fraction of the CDW, *El Mir et al.* studied the influence of the water absorption on the recycled aggregates, made by crushed bricks, in the replacement of the natural aggregates. The fresh properties showed a decreasing of the slump spread for the mixes with the recycled materials, due to the absorption of the water fraction. The same behavior was recorded for the mechanical properties. The compressive strength measured on the mixes showed the important decrease in the values in the case of full saturation for the recycled aggregates [45].

2.1 Recycling of C&DW

Since the self-compacting concrete was created in the 1980s by Professor Okamura, the research for materials that could in part replace the large fraction of fine aggregates has begun. The main purpose of these investigations is still to reduce the economic and environmental impact of the self-compacting concrete, obtaining a product with at least the same characteristics as the original. Recycling over the years has concentrated the attention to the substitution of the fine and the coarse aggregates, restoring the inert characteristic that requires. The main researches in the recycling inside this kind of concrete concentrated the attention to the wastes coming from the constructions and demolitions sector. The large quantity of wastes produced annually permits the recycling of materials with still interesting property and potentials.

Panda and Bal studied the behavior of a self-compacting concrete produced with the replacement of the coarser aggregates by demolition wastes. The recycled material was obtained by the demolition of a 25 years old town club building of Banki, placed in Cuttack region in east India. The analysis was performed on four different samples, with a substitution grade of: 10%, 20%, 30% and 40%. The specimens were classified in the following way:

- NCARR0: normal vibrated concrete with 100% of normal coarse aggregates;
- SCARR0: self-compacting concrete with 100% of normal coarse aggregates;
- SCARR0.10: self-compacting concrete with 10% of replacement by recycled coarse aggregates;
- SCARRO.20: self-compacting concrete with 20% of replacement by recycled coarse aggregates;
- SCARR0.30: self-compacting concrete with 30% of replacement by recycled coarse aggregates;
- SCARR0.40: self-compacting concrete with 40% of replacement by recycled coarse aggregates;

The results showed the increase of water absorption and a decrease of the density, with the increasing of the standard coarse aggregates replacement. This condition is caused by the old mortar still attached to the grains which influence the interaction with the water. The compressive strength, together with the flexural strength, presented a decrease with the increase in the amount of recycled coarse aggregates. However, after 28 days, the compressive strength of the samples up to 30% of replacement, achieved marginally the required value of the regulations. In Figure 4, are displayed the results of the tests performed on two kinds of shape samples: cubes and cylinders.

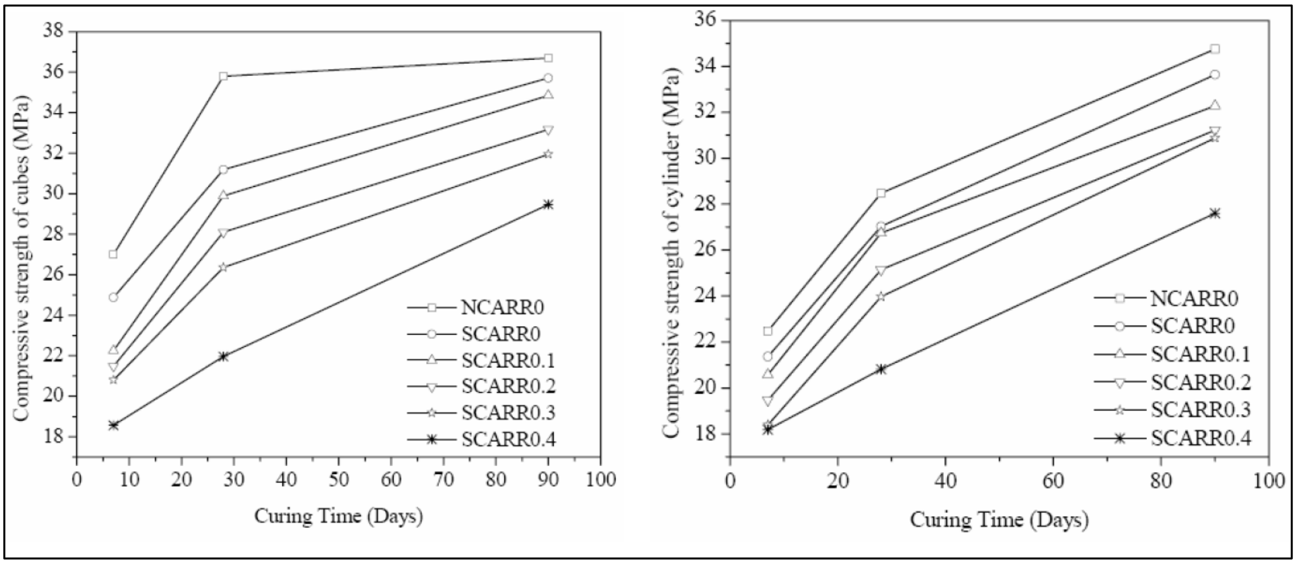


Figure 4: Compressive strength for the cube, on the left, and cylindric, on the right, specimens of different aggregates replacement [46].

The fine aggregates represent the larger fraction inside the composition of the self-compacting concrete. As for the coarser particles, is possible also for the fines the partial substitution by the recycled materials. Due to the major presence of the masonry and the concrete inside the C&DW (Table 1), some researchers started to investigate the recycling of this kind of materials.

Levy and Helène analyzed the influence of the recycling inside the composition of the self-compacting concrete by two different kinds of fines materials: the demolished concrete and the old masonry. The study was conducted on different samples made with the gradual substitution (20%, 50%

and 100%) of the river natural sand by the two types of materials. Three properties of the final concrete were monitored to investigate the variation made by the substitutions: the water absorption, the pore volume, the carbonation. The fine recycled concrete aggregates were obtained by the crushing of an old concrete structure. The physical properties of this concrete were well known before the analysis started. On the other hand, the recycled fines coming from the masonry were produced by the crushing of one-year-old brick walls covered with mortar, made of cement, calcium hydroxide and natural sand. The aggregates were divided by weight, respectively in 76% of clay brick and the remaining 24% in mortar [39].

From the results, the following conclusions were made. Considering the reference concretes made to achieve a final compressive strength between 20 and 40 MPa, the samples created with recycled aggregates showed the tendency to reach the same workability and compressive strength at 28-days. Due to the changes in the physical structure of the particles, the concrete made with the recycled aggregates presented an increase of the total pore volume together with a larger amount of water required.

The self-compacting concrete requires a higher amount of cement together with fines particles. This aspect represents an opportunity to investigate and analyze the recycling of fines particles coming from different industries, usually classified as a by-product, to replace part of the filler. The physical characteristics play the fundamental role to replace in the most suitable way the traditional material used. Generally, the recycled fines must guarantee an inert condition, to avoid any alteration in the process of hydration and hardening of the self-compacting concrete. However, in some cases, the material chosen can also influence the activity phenomena of the cement fraction.

Subaşı et al. have investigated the possibility of utilizing granulated waste ceramic filler like filler material inside the configuration of the self-compacting concrete. The cement fraction was substituted, on weight, in different percentages (5%, 10%, 15% and 20%) to study the properties variations during the fresh and hard state of the concrete. Due to the differences between the granulometry of the cement and the ceramic filler fractions, the recycled material was first grounded through the Los Angeles abrasion machine. Then, the material was sieved to recover the fraction below the 0.125 mm of diameter.

The analysis of the fresh properties showed the increase in the mix flowability with a substitution up to 15%. While for the case of 20% of cement substitution, the slump test showed less flowability, although the value is like the reference mix concrete. The addition of ceramic filler affected the density of the concretes, with a decrease of the value with the increase of the substitution rate (Figure 5).

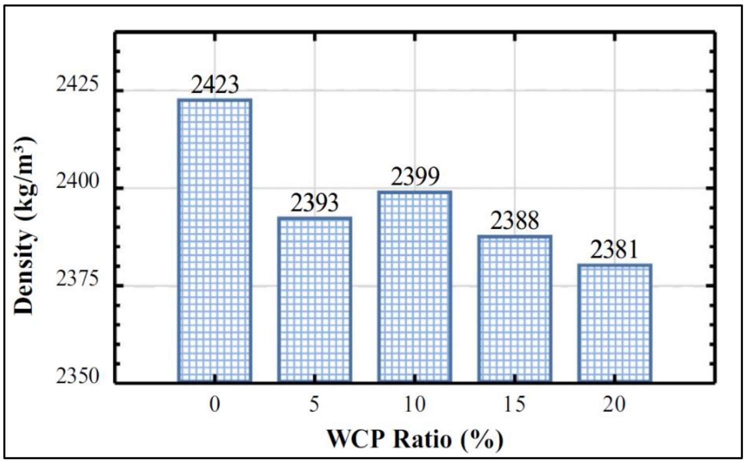


Figure 5: Density variation for the replacement of ceramic filler [47].

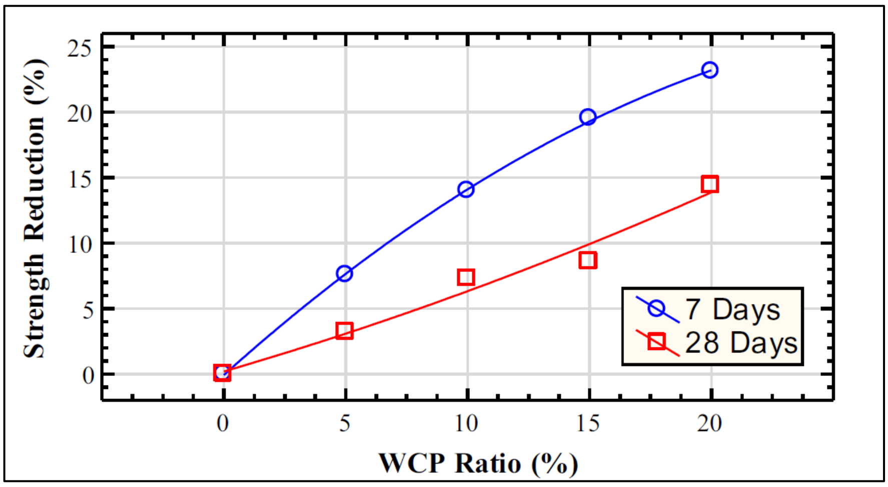


Figure 6: Compressive strength reduction according to the cement substitution [47].

Considering the hard-concrete state, the unit weight and the compressive strength for the specimens at 7 and 28 days from the mixing process were recorded. The unit weight showed a decrease with the higher amounts of ceramic filler. This is related to the low specific gravity of the recycled material respect to the traditional cement. Moreover, the reduction can be attributed to the incomplete hydration process in the mix and the higher creation of voids inside the concrete structure [47]. Generally, the compressive strength shown the gradual reduction of the final value with the increasing of the ceramic filler inside the concrete mix. The minimum value for the compressive strength was related to the 20% of substitution. While, the maximum was recorded for the reference mix, both in the 7 and 28 days cases (Figure 6).

The results justified the possibility of recycling the ceramic filler inside the production of the self-compacting concrete if the substitution rate of the cement is equal or under the 15% on weight. Indeed, in these conditions, the concrete had the most positive effects both on the fresh and hardened properties.

Regarding the recycling as filler by bricks, which are usually present inside the C&DW, *Mansor et al.* have analyzed the cement replacement by the ground clay bricks. The ground clay bricks used for the investigation were provided by the Al-Swani clay bricks factory. The aim of the analysis was to study the influence on the properties with the variations on the cement substitution by the ground clay bricks. Different mixes were produced with a replacement ratio between 0% and 50%, with an increment of 5%.

The fresh samples shown the increase of the water required for the mix with the increase of the ground clay bricks inside the samples. This condition is linked to the higher water absorption of the new recycled material, due to its different porosity than the traditional fraction. However, all the samples' values obtained from the slump-test were within the standard limits. So, in the end, the use of ground clay bricks produces important benefits for the rheological properties of the concrete, as the workability and the stability.

The results of the compressive strength tests at 28 days showed the decreasing of the values with the increase of the ground clay bricks content. This trend is related to the size of the bricks particles, in average 75 μm, which does not ensure a full hydration process in a reasonable interval of time. The less compressive strength is also caused by the higher amount of water necessary in the mix to face the absorption of the bricks particles. This condition leads to the decreasing of the mix density and the increasing of the porosity in the structure [48].

Abdulrazzaq et al. have studied, also, the fresh and hard properties of a self-compacting concrete with the cement replacement by a soft clay powder material, produced by the crushing of waste clay bricks. This substitution, on weight, was performed in three percentages: 5%, 10% and 15%. The powder of clay bricks was study through a characterization to understand its physical properties. The granulometric analysis showed a particles size distribution below 80 µm. While, the specific gravity and the water absorption coefficient, measured through the tests, were respectively 2.6 g/cm^3 and 26.6%.

The analysis on the fresh properties demonstrated that the replacing of the cement fraction by the clay brick powder can increase the slump spread and the height ratio detected in the L-box test. Moreover, the mix presented a decrease in the times recorded in the slump flow (t_{500}) and in the V-funnel tests. However, the increase of the cement substitution over 5% by weight causes a worsening of the fresh properties and, at the achievement of 15 % in the replacement, the self-compacting concrete does not reach the parameters range imposed by the standards.

The same trend shown by fresh properties is also found in the hard properties. In fact, with 5% of replacement by the clay brick powder causes the increase of the compressive strength both at 7 and 28 days, respectively of 1.1% and 2.7%. While, with 10% and 15% of replacement, the addition of the powder causes the worsening of the hard properties (Figure 7).

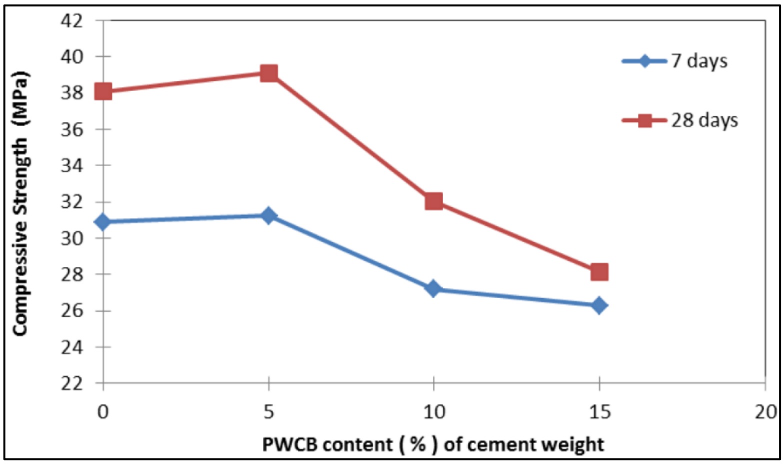


Figure 7: Compressive strength trend for the cement replacement by clay brick powder [62] .

2.2 Recycling in a Self-compacting mortar (SCM)

The analysis seen for the self-compacting concrete (SCC) can be applied also on the self-compacting mortar (SCM) to understand the possible influence of the constituents' replacement on the general properties [49]. However, even if with some differences, as the absence of the coarser aggregates, the trend of the mortar's properties follow, generally, the one presented by the concrete [49]. Therefore, the opportunities of the recycling in the self-compacting mortars are represented by the substitution of the sand and the filler fractions.

After the concrete, the bricks inside the masonry, represents the larger constituent of the C&DW. As for the investigations on the self-compacting concrete, also in the self-compacting mortar, the bricks together with the tiles and ceramics are commonly used to analyze their influence on the fresh and hard properties.

Aboutaleb et al. investigated the reuse of refractory bricks to replace the sand fraction in the production of a self-compacting mortar. The replacement, on weight, was performed with different percentages (0 %, 10%, 30%, 50%), to study the physical and mechanical of the mortar. The recycled refractory bricks were obtained by the demolition of an oven for the glass production placed in Algeria. The material was treated through crushing and sieving to reach a granulometry range between 0 and 5 mm. From the granulometric analysis of the refractory brick, a similar particles size distribution to the sand fraction was recorded. Moreover, the analysis on the shape of the bricks' particles showed the absence of round shaped granulometry which can permit a more efficient adhesion with the cement paste fraction [50]. The results of the properties for the fresh and hard mortars presented different variations compared to the control mix. The fluidity of the mortar started to decrease with the increase of the brick sand inside the mixes (Figure 8).

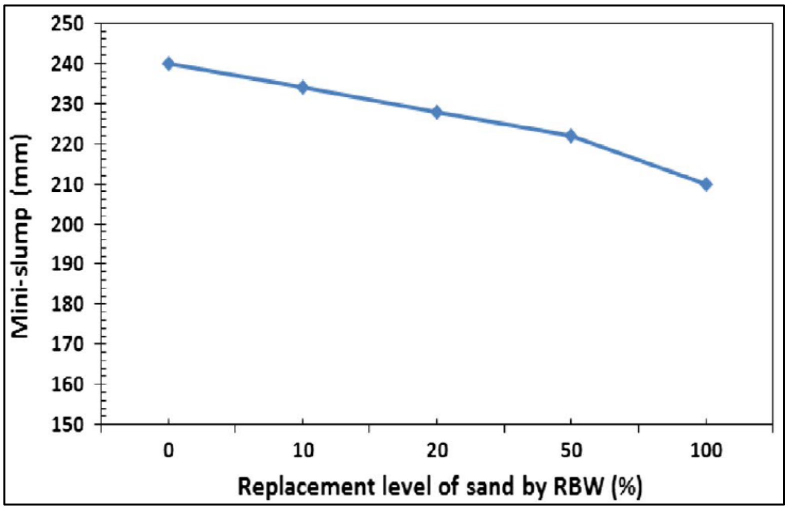


Figure 8: Slump-flow trend for the sand replacement variation [50].

This trend is generally caused both by the differences in the shape between the brick sand and the normalized sand's particles and by the higher water absorption by the recycled material [50]. This worsening of the fluidity can be faced through the addition of more superplasticizer inside the mix. However, the influence of the bricks particles on the apparent density of the mortars was negligible respect to the control mix, even if the recycled material showed an absolute density 20% lower than the traditional sand.

The study on the hard properties of the samples showed the decrease of the compressive strength with the increase of the sand replacement by the refractory bricks. Indeed, with the 100% of sand replacement, a decrease of the 13% was recorded respect to the mortar made by the natural sand (46 MPa). However, the value is still interesting for the constructions purposes, representing a valid alternative in economic and environmental terms.

After the sand, the filler material represents the major portion inside the self-compacting mortar, becoming an interesting opportunity for the recycling by the refractory bricks.

Abib et al. have investigated the effect of the crushed brick addition, as filler, on the rheological and mechanical properties of the self-compacting mortar. The waste clay bricks were coming from the production plant of Bejaia, in Algeria, and were ground up to reach the maximum diameter of 80 µm. The study was performed on samples of self-compacting mortar with the cement replacement, on weight, of 5%, 10% and 15%. The values coming from the analysis of the samples with the replacement were encouraging. From the Figure 9, is demonstrated that the mortar samples with the clay bricks presented a better performance of flexural strength and compressive strength respect to the other specimens. Moreover, the addition of the bricks filler inside the self-compacting concrete leads to the improvement of the rheological properties, such as the workability and the resistance to the segregation.

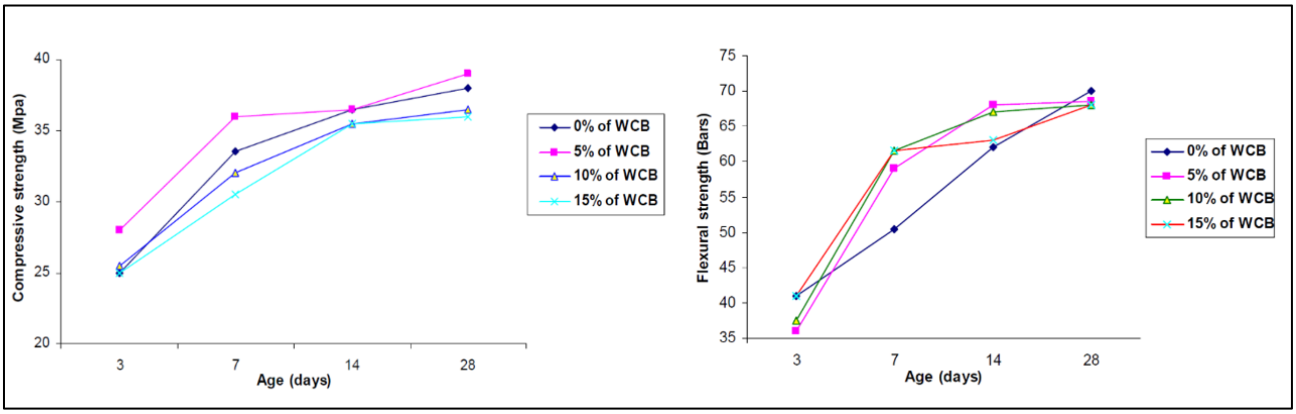


Figure 9: Compressive strength and flexural strength with the addition of waste clay bricks (WCB) [51].

Amjadi et al. have investigated the physical and mechanical behavior of the self-compacting mortar containing the most usual materials coming from the Construction and Demolition Wastes (CDWs) treatment. The study was based on the substitution on weight, of the cement fraction (for 5%, 10% and 15%) by the following recycled materials: the bricks, the concrete, the ceramics and the tiles. To reach the similar granulometry of the cement, the recycled materials were pulverized and sieved to obtain the granulometry range between 150 and 75 µm. The superplasticizer was used for the 1-2% of the cement weight to reach a slump flow of the samples between 240 and 260 mm. Regarding only the cement substitution by the recycled bricks, the following results on the fresh and mechanical properties were obtained.

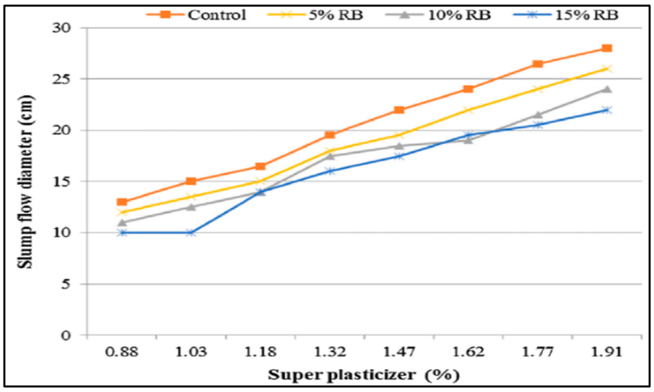


Figure 10: Slump-flow variation for self-compacting mortar made by recycled brick [52].

The slump-flow trend (Figure 10) displays the decreasing of the diameters values with the increase of the recycled material inside the mixture, as seen by the other researchers. Indeed, the more the recycled material are present in the mix, the more is the need for a higher amount of superplasticizer to achieve a significant slump spread. This behavior is caused by the higher absorption of the recycled fines compared to the natural aggregates which are usually used [52].

The reduction of the slump-flow, together with the linked flowability, can be partially solved by the resorting of the recycled materials through a pre-saturation stage before the mixing of the different samples of self-compacting concrete [52]. Moreover, the fineness of the materials used affect the flowability of the final mix causing a reduction of the diameter produced during the slump-tests (Figure 10).

The results of the mechanical properties pressented the general decrease of the compressive strength with the increase of material recycled inside the mortar. This trend is caused mainly by the low pozzolanic reaction of the recycled fines at the earlier time steps [52]. Indeed, the highest reduction of compressive strength was recorded, especially for the earlier intervals of time, in the mortar sample with a cement replacement of 15%. While, at the time step of 90 days, the mortar samples containing the brick filler produced a compressive strength comparable to the results obtained for the control mortar [52].

The analysis through the mercury intrusion porosimetry (MIP) was conducted on all the samples to evaluate the porosity, the distribution, the scale and the geometry of the pores. Thanks to this analysis, was possible to investigate the influence of the recycled materials on the matrix of the self-compacting mortars. For what concerns the substitution by the brick filler, the results presented the increase of the porosity with the increase of the percentage of replacement [52].

The recycling of the masonry materials, as for all the C&DW, both in the self-compacting concrete and in the self-compacting mortar represents a great occasion for the decrease of the raw materials exploitation and the reduction of the economic and environmental drawbacks. Moreover, the researches presented previously demonstrated the feasibility. However, this type of mortar and concrete, even with the recycled materials inside, must guarantee the same behavior and characteristics of the one produced with the traditional constituents. In the following chapter, for this reason, will be presented the main features of the self-compacting concrete which has to be followed by the mix containing the recycled elements.

3. The Self-Compacting Concrete (SCC)

The most used material in the construction phase of a building, with a worldwide production of more than ten billion tons per year [53], is the concrete. It can be classified as a heterogeneous mix, composed of substances in different percentages of volume and weight. The main constituents inside it are: the aggregates, the sand and the cement paste. Each of these fractions acts for a specific aim. On one hand, the aggregates together with the sand ensure the consistency and the strength of the mixture's volume, while the paste fraction behaves as the hydraulic binder.

Usually, some additive products are added in little quantities to modify the behavior of the mix. For instance, these type products can be used to increase the fluidity, reducing the water required, to delay the hydration of the cement fraction, or to purposely introduce and stabilize microscopic bubble of air inside the mix, facing the frost action by water.

In the '70s, especially around Europe, a type of concrete which did not require the vibration was already used and exploited, until in the late 1980s when were developed researches and studies in Japan about the self-compacting concrete (SCC). Precisely, in 1986, the first prototype of this innovative type of concrete was produced by the Professor Hajime Okamura for mainly two reasons. On one hand, the satisfactory workers' skills required for the compaction phase of a durable concrete and, on the other one, the gradual reduction of the workers themselves for the construction industry.

3.1 Advantages & disadvantages

The self-compacting concrete, also named as self-consolidating concrete, self-leveling concrete or vibration-free concrete, is an innovative concrete which does not require the use of vibration during the placing for its compaction. Thanks to its fresh properties, it can flow under its weight, filling all the space available, reaching the full compaction, without any influence on the sliding by the presence of reinforcements [54].

When this innovative type of concrete was ideated, the objective was to simplify and improve the quality of the structures modifying the composition of their main constituent. However, as it is generally the case for all the technological innovations, the choice to exploit its improvements creates, also, problems that were not normally present in the traditional options.

The main advantages, from a technical point of view, about the usage of the self-compacting concrete are summarized in the following concepts.

Improvements on the structure

Thanks to the different composition, respect to the traditional vibrated concrete, the final product gains a higher durability in terms of time. This is linked to the extra compactness, due to the higher packing density of the particles and the higher filler presence, which leads to the decrease both of its permeability and of possible superficial imperfections [55]. In the hard state, it results in an improvement of the superficial surfaces, leading to structural and aesthetic benefits. So, the choice of the self-compacting concrete leads to higher quality and more visually pleasant buildings [56]. These new features help the concrete to have less weak points on the surfaces which could be attacked by the environmental agents in the surrounding area. Because of the high filler presence in the composition of the self-compacting concrete, the segregation is avoided during the cast phase in the site.

Moreover, the absence of the vibration phase before the hard state allows the design of more complex structure, which requires harder operations during the casting process. This permits also to have more freedom in the design and the shape of the building projected [57].

Economical improvements

The absence of the vibration phase during the erection of the structure permits to save time in the timetable of the project, making the construction faster. Moreover, the manpower which should be used for the vibration process can be employed for other operations, increasing the efficiency of the construction [57]. The vibration step absence and the unused workers represent a saving on the costs of the required equipment and materials. These aspects are fundamental for the already developed countries, where the target is to decrease as much as possible the labor costs and the schedules for the constructions. Moreover, the choice of the self-compacting concrete leads to overall energy savings when the concrete is placed on the work site [58].

However, this type of concrete starts to be convenient for the construction industry when there is the requirement of big and complicated constructions where the vibration stage can be difficult to be performed.

Environmental benefits

In the last decade, the environmental aspects have become more dominant in the construction industry to reach the possible least impact on the surrounding area. The self-compacting concrete represents an option environmentally convenient. Indeed, even if its first purpose is to simplify the construction of complicated buildings and reduce the employers for the placing procedure, its creation has led to several benefits for the environmental aspects. The elimination of the vibration step brings not only the savings in terms of energy costs but also the improvements in the quality of the works. Indeed, the absence of the vibration guarantee the production of less noise pollution which could affect the surroundings areas [59]. Moreover, due to the absence of vibration process, the use of the self-compacting concrete guarantees the reduction of the dust levels inside the work site [60]. Due to the need of an important filler portion, the use of the SCC can lead to the recycling of materials usually defined as by-products. They, thanks to their chemical and physical properties, can be inserted in the composition leading to the achievement of the similar fresh and hard properties of the reference self-compacting concrete. Furthermore, the replacement of the cement fraction can reduce the carbon-footprint of the produced concrete [58]. Indeed, since the cement production does not represent an environmentally friendly industry and the material re-used are considered as by-product, the recycling of the fillers may lead to the dual benefit.

The advantages presented for the self-compacting concrete are demonstrated only in isolated situations and projects. However, as all the types of products and material, also the self-compacting concrete present some drawbacks related to various aspects [61]:

- The addition of filler fraction inside the composition, together with the cement, is needed, leading to the increase of the costs, due to the price of this materials;
- The self-compacting concrete shows a higher sensitivity to the changes in the mixture components, like the saturation of the sand fraction or the variation in the aggregates' features;
- The superplasticizers used generally to improve the workability of the mix, increase the final cost of the product, due to their high price;
- The lower ratio between the water and the cement, together with the higher content of fine aggregates, increases the sensitivity of the concrete to the shrinkage phenomena;

3.2 Mix composition

During the production of the fresh self-compacting concrete, the selection phase for the mix composition and the proportions of the constituents plays an important role on the final physical and mechanical properties of the product. Moreover, due to the differences from the traditional one (Figure 11), the variation on the admixture portion in the production can affect or improve more the behavior of the concrete.

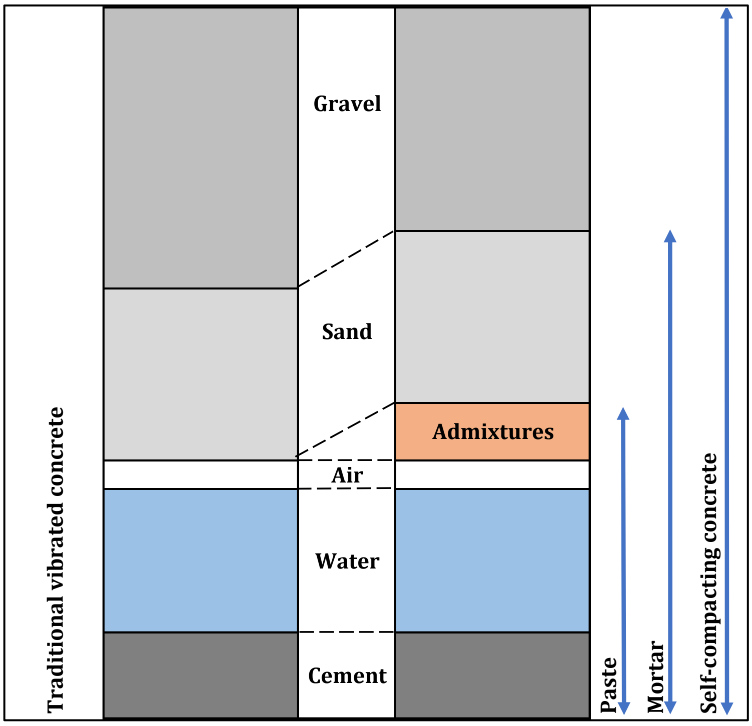


Figure 11: Mix composition comparison for the traditional vibrated concrete and the self-compacting concrete.

The main components used in the production of the traditional vibrated concrete are the same ones that can be employed in the self-compacting one, satisfying the norm EN 206-1. However, as already presented, there is a difference in the paste portion with the addition of an admixture part. Each element, if not carefully selected, can subsequently affect the properties and, then, the use and the application of the concrete itself.

The constituents commonly used for the SCC production may be classified in the followings [62].

The cement

The choice of the type of cement in the mixture is strictly dependent on the application and the performances required for the concrete. In the case of the self-compacting concrete, it may represent a sensible selection, because of the larger presence of filler which could affect the hydration process of the cement. From the European guidelines for the production of SCC is specified that all the cement filler which satisfy the requirements of the norm EN 197-1 can be employed [55];

The mineral admixture

Usually, the admixture may be used in the mixture to modify the fresh state behavior of the concrete. Generally, the additives used more frequently are the superplasticizers and the viscosity modifiers. The first ones are used to increase the fluidity of the fresh concrete, leading to a decrease in the water content within the mixture. On the other hand, the viscosity modifiers, as the name suggests, guarantee a change in the cohesion of the concrete self-compacting without affecting the fluidity, and therefore the workability. Moreover, the latter can be used to make the mortar less sensitive to the variations of the aggregates size. In some conditions and situations, the building project requires the use of the air entraining additives. These compounds allow the significant formation of air bubbles inside the cement paste fraction. Thanks to this large presence of air inside the solid matrix, the self-compacting concrete can guarantee a higher durability to the freeze-thaw cycles which may occur in particular environment [62]. The choice of the admixture to insert into the self-compacting concrete can be influenced by the physical and chemical features of the binders or the filler additions usually present in this kind of concrete. The admixtures are generally very steady from a batch to another. However, when the manufacturer or the type of the admixture is changed, it is likely to face some significant changes on the self-compacting concrete behavior. For this reason, it is recommended to check the possible differences produced by the modification of admixture.

The additions

It is normal, due to required fresh properties for the SCC, to add inert, pozzolanic or hydraulic additions inside the mortar fraction. Indeed, they are commonly used to modify and improve the fresh behavior of the concrete. The additions are commonly chosen to increase the cohesiveness between the aggregates and the cement paste together with the reduction of the segregation possibility during the placing phase. Generally, this kind of materials are used to reduce part of the cement portion to decrease the heat produced by its hydration and the possibility of thermal shrinkage [62]. The mineral fillers are additions which are commonly used inside the self-compacting concrete. However, their water absorption, their granulometric distribution and the shape of their particles may influence the amount of water needed inside the mix and, therefore, their suitability to produce the concrete. Another addition already studied to produce the self-compacting concrete is the fly ash. It has been presented by the results of several studies to be effective on the properties of the SCC, guaranteeing a cohesiveness improved and a reduction of the sensitivity for the water content. Nevertheless, if the content of fly ash inside the mix is too high, the paste fraction can be so cohesive that it can become resistant to the flow.

The silica fume represents another choice as addition to the self-compacting concrete. Indeed, thanks to the spherical shape of the particles and their fineness, the concrete can achieve a good cohesion and a satisfactory resistance to the segregation. In some other cases, the ground granulated blast furnace slag is used as additions thanks to its fineness and low heat by hydration. Also for this type of addition, if the quantity is too high it can lead to the stability decrease of the SCC, reducing the robustness and increasing the possibility of segregation.

The aggregates

The coarse aggregate together with fine ones, represented by sand, constitute the larger portion in terms of volume on the entire mix of the concrete. The water absorption together with the content of fine particulates and the particles size distribution should be checked constantly, to maintain satisfactory properties of the concrete. Moreover, the saturation grade of the aggregates, as demonstrated by several studies, may have a positive effect on the consistency of the product [62]. The shape of particles covers also an important role on the final packing density and on the voids content of the concrete. As seen for the admixture case, the changing of the aggregate supplier can have a significant influence on final concrete properties. For this reason, is common the checking of the differences with the variation in the type of aggregates. In general, two kind of aggregates can be classified:

- *Coarse aggregate:* All aggregates which guarantee the properties described in the European standard EN 12620, can be used inside the production of the self-compacting concrete. The shape, as already said, with the particles size distribution, represents the main parameter which can influence the workability and the passing ability of the fresh concrete. The choice of the dimensions' range is reliant on the position and the presence of reinforcements in the structure, which could affect the passage of the grains. Generally, the maximum size for the coarse aggregates stays between 16-20 mm, but this can change according to the application [54];

- *Fine aggregates:* The fine aggregates, compared to the coarser ones, have a significant influence on the fresh properties of the SCC. In fact, the excessive presence can lead to a mixture too much resistant to flow, because of the internal frictions between the various components. For this reason, the cement paste must be present in a high volume to ensure the reduction of the internal friction between the fine particles. However, some method for the SCC production suggests using blended sands, ensuring an optimal grading curve and reducing in this way the paste fraction content.

The mixing water

The quality of the water used in the concrete preparation plays a key role in the composition. Indeed, its improper choice could produce defects of aesthetic nature in the final work, creating problems in the socket of the concrete on the reinforcements or, in the worst cases, causing a gradual worsening of the mechanical properties of concrete itself. For these reasons, the water that is chosen during the work must first comply with the parameters presented in the European legislation EN 1008. The analysis to be carried out following the regulations must ensure that organic pollutants, surfactants, oils or acid substances are absent. The presence, even in small quantities, of these substances can cause the delays in the hydration of the cement, the excessive air incorporation, the slowdown in the development of mechanical properties and the reduction of adhesive forces between pasta and aggregates.

However, after the theoretical design of the concrete, the laboratory trials and tests must be used to verify the achievement of the properties more suitable for the employment. With the analysis of the first results from the test, some adjustment can be made to ensure the reaching of the properties required. Then, the concrete can be tested at the concrete plant and, if it is necessary, at the work site before the placing phase. The design process of the self-compacting concrete can be summarized in the following phases [62]:

- Estimation of the water addition and improvement of the flowability and stability of the paste fraction;
- Evaluation of the quantity of sand and admixture to ensure the appropriate robustness;
- Analysis of the concrete sensibility to small changes in the composition;
- Choice of the appropriate quantity of coarse aggregates;
- Study of the fresh and hard state of the SCC through the test in the lab;
- Production of the mixes trials before the placing phase;

All these steps are part of the following scheme (Figure 12), where the procedures for the achievement of the pre-fixed properties of the SCC are summarized.

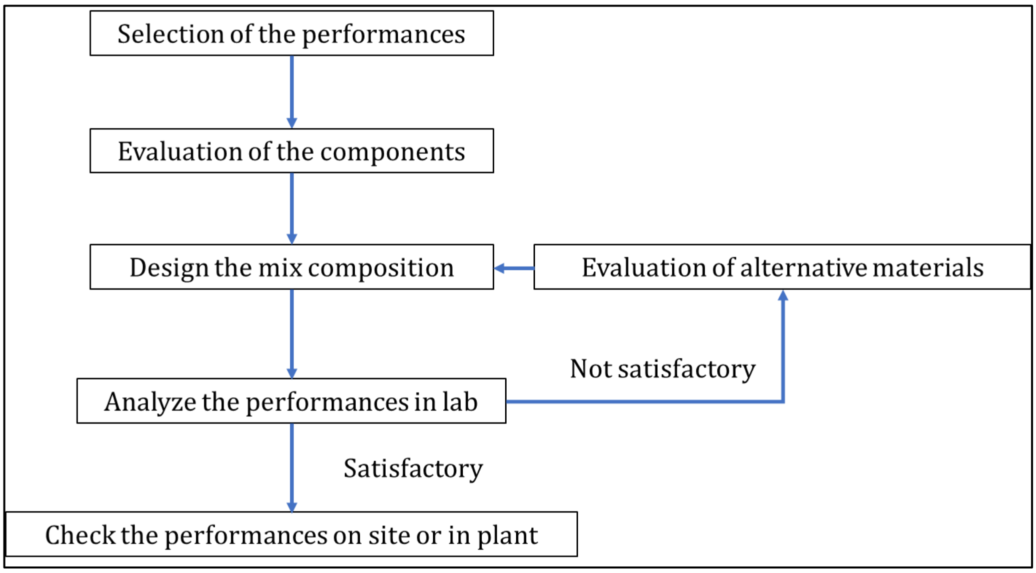


Figure 12: The flowsheet for the design process to produce the self-compacting concrete [62] .

3.3 Properties of the self-compacting concrete

The main properties of self-compacting concrete are the fresh state and its behavior. The placement and the compaction are the main aspects which are influenced by the characteristics of this type of concrete. The self-compacting concrete distinguishes itself from other concretes for the filling ability, the segregation resistance and the passing ability. As will be shown, these characteristics are interdependent to each other. For instance, the low segregation, together with high filling ability, allow a satisfactory passing ability.

Filling ability

The filling ability can be defined as the tendency of the concrete to flow and, then, fill the formwork placed in the site work, helped only by the gravity. The self-compacting concrete which shows this kind of feature is the one that can change its shape after the action of its own weight. The filling ability is dependent both on the capacity and on the deformation speed. The first can be defined as the maximum ability to deform, while the deformation speed is the time needed by the mix to stop flowing [63].

This concrete feature can be modified, reducing the friction between the grains of the aggregate. Theoretically, the addition of more water in the composition is not the most suitable way to achieve this objective. The rise of the water fraction, indeed, can cause the segregation in the mix, due to the fall of viscosity. Moreover, an excess of water, that cuts the ratio between water and cement, can affect the final strength and durability of the product. The use of water in order to reduce admixtures, like the super-plasticizers, can reduce the friction between the grains maintaining the filling ability [64]. The distribution of the particles size inside the composition can influence the filling ability. The coarser aggregates can affect the flowability of the concrete, while the reduction of them can decrease the friction between the grains [64].

Passing ability

The passing ability represents a unique property of the self-compacting concrete and it defines the tendency of the fresh mix to flow through restricted or tight openings without any blocking phenomena. This guarantees its application in structures characterized by important reinforcements. When the concrete starts to pass through the tight space, the different velocity of the fractions leads to an increase of the coarse aggregates content. The interaction between grains can affect the passing of the concrete causing the blocking of the material [65].

The main parameters which influence this phenomenon are the particles shape, the size and the content of the coarse aggregates. The presence of finer aggregates together with higher paste volume can guarantee the improvement of the passing ability [66]. However, also a good viscosity can reduce the coarse aggregates quantity in the tight opening, avoiding the blocking process. The increase of the viscosity is achieved by the incorporation of filler materials which produce a better grain distribution and packing of the particles [67].

Segregation resistance

The segregation is the tendency of the components, inside the self-compacting concrete mix, to migrate and be separated. Usually, the different diameters and densities of the aggregates are the main features which influence the possibility of segregation. Indeed, the components with the higher density are more prompt to the separation from the paste. This property becomes fundamental for the homogeneity and the quality of the self-compacting concrete placed in the work site [63].

The phenomenon can happen in dynamic and static conditions. The first takes place when the mix is transported and placed in the formwork of the work site. While, the second, starts when the concrete is already in the formworks to start the hardening process.

If the concrete is characterized by the segregation, the final product can be affected through surface defects and non-homogeneous structure, when the material is hardened. To face this problem, the viscosity must be increased. This can be achieved through the reduction of the ratio between water and cement, by the utilization of higher volume of filler materials or with the use of viscosity modifying agents. Moreover, the reduction of the coarser aggregate fraction prevents the segregation phenomena [63].

In the end, the self-compacting concrete, thanks to its composition, has different properties compared to the traditional vibrated concrete. Generally, the self-compacting concrete production is based on several principles, which, if well followed, can lead to an acceptable product for the construction sector. However, the presence of admixtures and compound agents, for the fresh and hard properties modification, is a delicate aspect which must be monitored during the production phase to ensure the pre-fixed characteristics.

3.3.1 Self-compacting concrete principles

Generally, during the design phase of the construction, with the choice of the type of concrete that will be used, specific parameters need to be respected. Indeed, during the prescription of any kind of concrete, the norm EN206-1: 2001 "Concrete – specifications, performances, production and conformity" is taken as reference for the analysis [68]. This document provides guidelines and the conformity for each constituent to formulate a concrete which comply with the European Union regulation. Therefore, four main parameters must be found, according to the case of study in consideration, to be then used to produce the concrete.

1. The maximum amount of aggregates

During the production of the liquid concrete, the main physical properties of the fresh state can be affected by the quantity of aggregates added to the mix. Indeed, the workability and the passing ability of the concrete are influenced by the shape and the granulometry range chosen. On one hand, the round shaped particles help to reduce the friction between aggregates and improve flowability. This, in fact, can lead to an increase in the energy required to flow the mix in the appropriate spaces, then translating into stress inside the structure. On the other hand, the decreasing of the average granulometry leads to the increase of the passing ability of the fresh concrete in the reinforcements usually present in the structures. These precautions must be taken to lower the relative distance between particles, and consequently, to decrease the frequency of contacts and collisions between the aggregates [65].

2. The water cement ratio

The ratio between the water mixing and the filler fraction covers a fundamental role in achieving a satisfactory fluidity and viscosity of the paste. The high viscosity is required to avoid any phenomenon of segregation during the casting of the concrete and to ensure the carrying of the aggregates during the flowing. If the material has a low viscosity during the placing phase, the coarse aggregates could start to be segregated by other fractions. However, a high ratio between water and cement can increase the workability of the fresh concrete due to the gain of more flowability. These aspects are, however, linked to the nature and the volume of the coarse aggregates and the sand [64]. Nevertheless, the increase of the water-filler ratio can worsen the mechanical properties in the hard state. In general, the water-filler ratio is in the range of 0.9-1.0 in volume but can vary depending on the type of material used for this fraction. On the other hand, a ratio between 0.84-1.07 is an ideal range for the production of SCC [69].

The high ratio between water and cement can be achieved through the addition of a large amount of filler materials, which can also have a positive effect on the filling ability of the concrete [70]. A more expensive way to increase the paste volume inside the concrete structure is through the use of viscosity modifying agents. These compounds, besides increasing the viscosity of the concrete, guarantee the reduction of the segregation of the coarse aggregates thanks to the thickening of the paste and the water retention in the mix. Moreover, the use of this admixture can lower the sensitiveness of the self-compacting concrete to the water variation [63].

3. Superplasticizer influence

To achieve a high deformability and a satisfactory workability of the mix, together with a constant viscosity, of the fresh paste, the use of the superplasticizer must be considered. The superplasticizers act like a dispersant which causes the spreading of the possible flocculated cement particles and a reduction of the agglomeration derived by the attractive forces. However, the use of this type of compound to increase flowability can make more likely the segregation for the coarser fraction of the aggregates, if used in high dosage during the production phase [71]. The content of this agent is related to the coarse and fines aggregate contents to guarantee the compactness of the fresh mixture under its own weight. A low viscosity, due to the high fraction of superplasticizers can lead to a disproportion of the aggregates' distribution, with more concentrated zones near to the obstacles, usually represented by the reinforcements [63].

A concrete mix can be defined as self-compacting only if the three properties, linked to the workability, are verified: the passing ability, the filling ability and the resistance to the segregation [72]. Although all the properties must be present in the mix simultaneously, there is not a unique test method which allows the determination of all the workability aspects at the same time. For this reason, the mix must be analyzed through different tests, specific for each property.

3.4 Tests for the SCC

The analysis on the fresh state of the self-compacting concrete cannot be performed through the same methods used for the normal vibrated concrete. The sensitiveness of the traditional tests is not sufficiently high to detect a possible segregation.

Following the European guidelines, a specification for the analysis of the concrete properties is given through the norm EN 206-1. The tests can be classified both as qualitative and quantitative. The qualitative analysis of the self-compacting concrete gives a general description of the properties without any technical study on the filling ability, segregation resistance and passing ability. On the other hand, the quantitative tests allow the description of the self-compacting concrete behavior and the measurement of the rheological properties, as viscosity and yield stress [63].

Slump flow test

The slump flow test is one of the most common and used ways for the evaluation of the deformation ability of the concrete. Through its own weight, the slump spreads of the mixes are analyzed. The test is performed with the absence of obstacles and restrictions to identify the friction on the base of the material cone. This kind of test can be useful for the study of the segregation tendency for a concrete. Indeed, through the study of the cone of material, the separation between the paste and the aggregates can be detected. Thanks to the result, made on the diameter value, the filling ability is quantified, while the time needed for reaching of 500 mm of spread (t_{500}) is used to evaluate the viscosity of the mix. The test procedure is very simple and can be performed directly on the site to verify the consistency of the self-compacting concrete, before the placing phase.

The device used for the test consists in a truncated cone conformed to the norm EN 12350-2, named Abrams cone, with the diameter at the top of 100 mm, the diameter at the bottom of 200 mm and a height of 300 mm. Then, Abrams cone is placed on a stiff plate made by a non-absorbing material to avoid any alteration on the result (Figure 13).

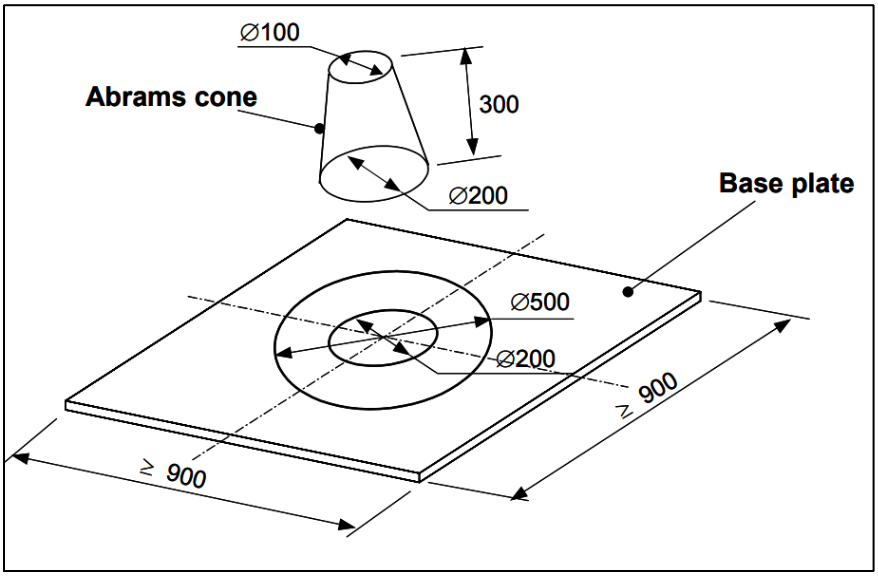


Figure 13: Slump flow equipment [73].

According to the European guidelines (2005), the EFNARC (European Federation of National Associations Representing for Concrete) suggested tree classes of concrete, based on the slump spread (Table 3). The SF3 class presents the highest spread, therefore also the highest workability and filling ability. However, the mixes categorized with this class could present some segregation behavior. On the other hand, the SF1, due to the lower spread interval, is linked to the mix with a lower workability [62].

SCC class	Slump spread (mm)
SF1	550-650
SF2	660-750
SF3	760-850

Table 3: Slump flow classes according to the slump spread [62].

V-funnel test

This test was developed first in Japan and it is used for evaluating the filling ability for a self-compacting concrete. The V-funnel is filled with a fixed quantity of material usually 12 liters, and the time needed by the mix to flow through the device is recorded ($t_{v\text{-funnel}}$). The shape of the device used in the test allows the detection of the blocking phenomena, which happen with the high content of coarse aggregate and the high viscosity of the mix (Figure 14). If the time recorded shows a low value, the mix has a high filling ability due to its low viscosity.

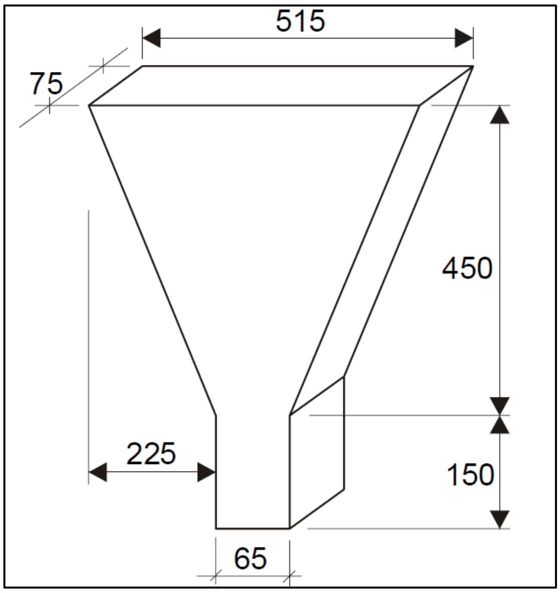


Figure 14: The V-funnel device [73] .

As for the slump flow test, also for the V-funnel the EFNARC has defined two classes of mixes based on the t_{500} value and the V-funnel time ($t_{v\text{-}funnel}$), displayed in Table 4.

SCC Class	t_{500} (s)	$t_{v\text{-}funnel}$ (s)
VF1	≤ 2	≤ 8
VF2	> 2	9-25

Table 4: SCC classes for the V-funnel test [62].

J-ring test

Contrary to the two previous tests, the J-ring test is used to investigate both the filling ability and the passing ability of concrete self-compacting. In addition, the results of this test can be interpreted to analyze the resistance to segregation. The combination of the results obtained for the slump flow test and the V-funnel test allows a better understanding of the filling and passing ability of the concretes analyzed. The parameters recorded during the test are the time required by the mix to reach the 500 mm of spread diameter (t_{500J}) and the range required to reach the blocking step (B_J).

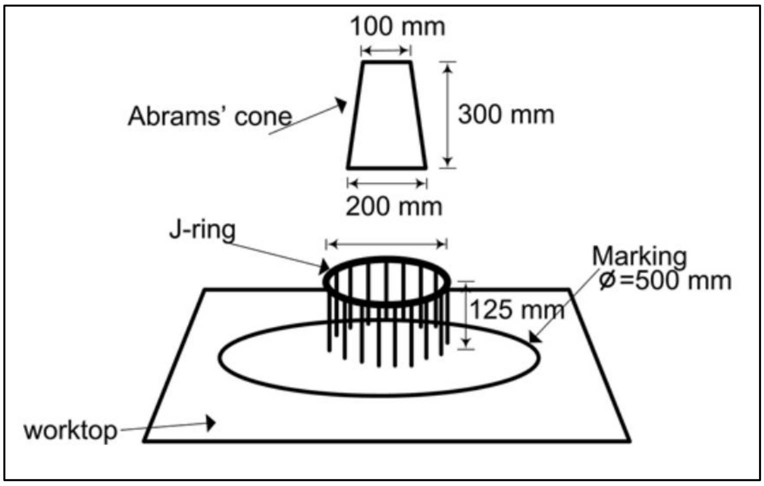


Figure 15: Test apparatus for the J-ring test [52] .

The tools used for this type of test consists of the Abrams cone, which has the same dimensions exposed before presented, a base plate, made of a material possibly non-absorbent, and an open steel ring, with a diameter of 300 mm, which has vertical reinforced bars on it (Figure 15). The Abrams cone is placed at the center of the steel ring and it is then filled with the fresh mix, without any compacting action. Then, the cone is lifted and the concrete can spread on the base through the vertical bars. In the end, the spread diameter is recorded as done for the slump slow test. The differences between the height of the concrete near the vertical bars and in the center of the concrete spread are recorded in four different positions outside the j-ring. The final difference of height between the average of the four points outside the j-ring and the center of the concrete spread is the blocking step. If this value is near zero, it means that the self-compacting concrete tested has satisfactory passing and filling abilities [72].

According to the EFNARC specifications (2002), a blocking step between 0 and 10 mm can be taken as an acceptable value for a satisfactory passing ability of a self-compacting concrete [72]

L-box test

This kind of test aims to investigate the passing ability and the resistance to the segregation of a self-compacting concrete mix. It consists of an L shaped box, with a rectangular section, with vertical and horizontal parts. These two sections are separated by a movable gate, after which reinforced bars are placed (Figure 16). The vertical part is filled by the self-compacting concrete, after being wetted in its internal surface walls. Then, the gate is lifted vertically to permit the SCC flow through the reinforced bars. When the flow stops, the heights in the vertical (H_1) and the horizontal (H_2) sections are measured. The ratio between these two values (H_2/H_1) gives the blocking ratio. The more this value is near the unity, the better are the passing and filling abilities of the mix tested [72].

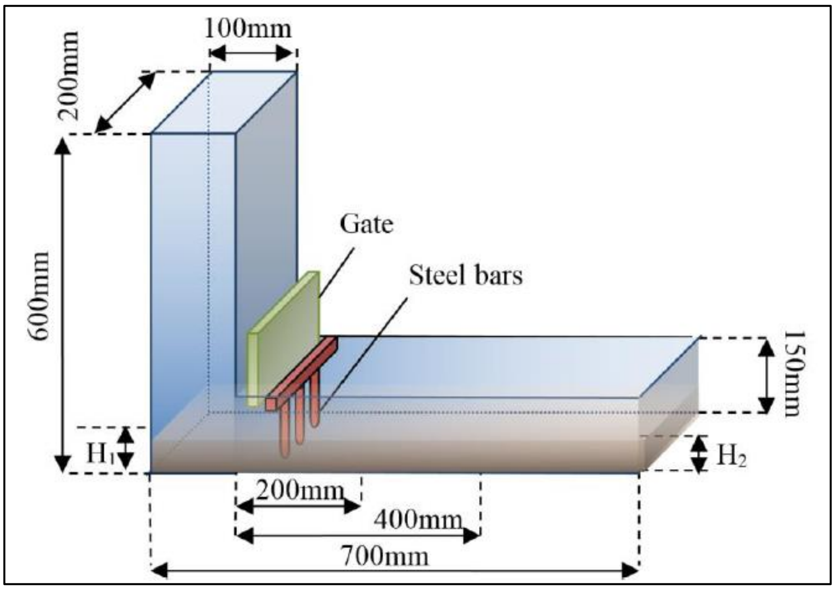


Figure 16: L-box test apparatus [63].

The horizontal section of the L-box tool can be marked at 400 mm and 200 mm to measure the time needed by the SCC to reach these two distances. However, according to the EFNARC specifications (2002), blocking ratio of the mix is between 0.8 and 1 is considered satisfactory. For what concerns the segregation resistance, a visual inspection can be carried out on the spread of the concrete. If coarser aggregates are detected on the surface of the mix and the distribution is uniform in all the direction of the horizontal section, the SCC possesses an adequate segregation resistance [72].

However, these tests, based on the analysis of the self-compacting concrete, will not be performed in this specific study. The investigation, indeed, will be conducted on a self-compacting mortar mix, so the assessments will be slightly different. Thanks to the method of the concrete equivalent mortar (CEM) presented in the following chapter, it will be possible to relate the results obtained for the mortar to the possible concrete mix containing the same paste inside.

4. Objectives and methodology

After concrete, the masonry materials (bricks, tiles and ceramics) are the largest fraction inside wastes produced in constructions and demolitions [13] in Europe. This study investigated the potentiality of the waste bricks recycling inside the production of a self-compacting mortar, without the presence of superplasticizer to ensure a clearer detection of bricks' behavior. The main objective was to understand how a partial substitution of limestones fractions with waste bricks might affect the physical and the mechanical properties of the final self-compacting mortar.

The investigation was conducted through the partial substitution of two mains limestone fractions inside the self-compacting mortar: the filler and the sand. The replacement was carried out by volume, and not by weight, since bricks and limestone have different density.

The first step was to prepare and treat the waste red bricks to achieve similar physical properties as those of the limestone sand and those of the limestone filler used inside the self-compacting mortar production. Through several crushing treatments and sieving procedures, the recycled material was modified in the granulometry to be as similar as possible to the limestone materials.

Subsequently the recycled materials were characterized. On one hand, the study on the physical properties of the waste bricks was conducted to acquire a better knowledge of their features. On the other hand, the behavior recorded during the analysis of the mortar and the differences between the mixes were better understood. The treatment was performed to obtain two different kinds of material made of waste red bricks. The first, a brick filler, with a granulometry under 100 μm and, the second, a brick sand with the particles size distribution between 0 and 4 mm.

The investigation was then concentrated on the differences between the brick filler and the limestone filler in the production of the self-compacting mortar. Later we analyzed the differences of the mortars produced replacing partially the limestone with brick sand.

The choice of the mortar mixes is based on a method called concrete equivalent mortar (CEM) developed by Schwartzentruber and Catherine [49]. It is based on the hypothesis that there is a link between the rheological properties of a concrete and the mortar which is inside it. In this way, the mortar tests are possible, and the results obtained are valid also for a concrete composition made with the same mortar. Its main advantages are the rapid performance of several tests, with fewer elements than for concrete tests, and the use of a standard material. The slump spread values produced by the CEM mortar (via a mini-cone) can be correlated to the results found with the Abrams cone on the concrete.

The mortar equivalent of the concrete must have the following characteristics:

1. The same type and dosage of cement as for concrete;
2. The same type and dosage of mineral additions;
3. The same water-cement ratio, as shown in Figure 17;
4. The same type and dosage of additives;
5. The same introduction method during the mixing procedure;
6. The same quantity and type of sand of the concrete;
7. A quantity of sand to reach the same surface area of the gravels removed;

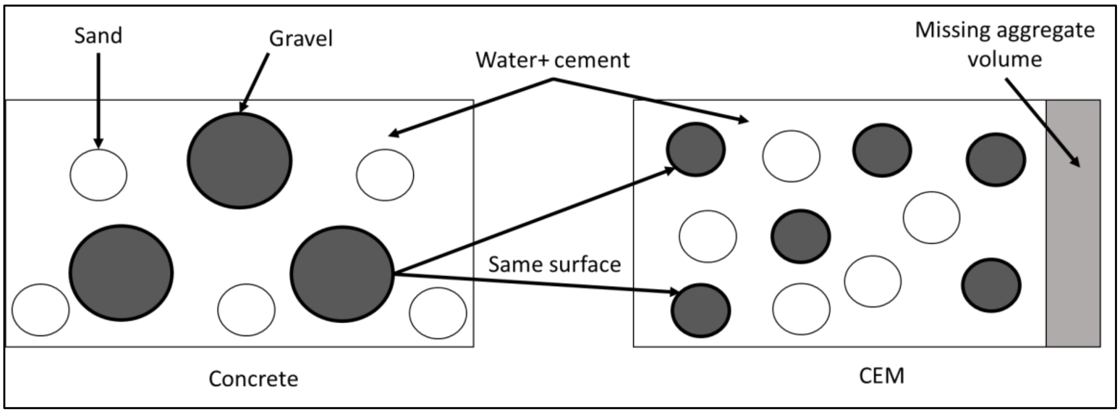


Figure 17: Conversion from concrete composition to CEM mortar [74].

Giving the fact that the sand has a higher surface/volume ratio, the quantity required to arrive to the same granular surface is lower than that of the aggregates (Figure 17) [74]. The transition from a concrete to its equivalent mortar originates a reduction in the granulometry and an increase of the distances between particles. This behavior takes place only when coarse aggregates have small fractions of particles with a diameter lower than 5 mm. If this is not the case, these particles must be separated through the sieving of the concrete and inserted into the mortar composition. However, the correlation between the mortar's behavior and the equivalent concrete is not always valid and constant, but it must be analyzed experimentally for each case study [49].

In the first part of our case study on the mortar, we choose two percentages of limestone substitution: 50% and 100% each with a different amount of water Indeed, for the first two mixes, named W.A., the quantity of water added was decided considering the possible absorption of the brick material. While, the other two mixes, named N.W.A, contained only the water needed for the hydration process of the cement. After evaluating the rheological and fresh properties of the mortars produced, we measured the mechanical and hard properties of the mortar samples at 7 and 28 days. The results were then compared to detect the possible improvements or worsening of the mortar.

The same investigation was conducted on a self-compacting mortar produced with the gradual limestone sand replaced by the brick sand. The rheological and the fresh properties were first studied with the following substitution percentages: 0%, 5%, 10%, 25% and 50%. Then, we analyzed the mechanical and the hard properties after 14 and 28 days for the replacement percentages of 0%, 25% and 50%.

As said previously, however, the first step in the recycling of the waste red bricks was the preparation and treatment phase. The modification of the material, in this study, played the main role in the achievement of the right physical properties for the comparison with the limestone sand and the limestone filler. Since each process can influence the results on the mortar analysis, the procedures must be monitored as much as possible to ensure the satisfactory production of the brick sand and the brick filler.

4.1 Materials and Testing

4.1.1 Materials preparation

The material used for this study is composed of waste red bricks coming from the production of the Barry division plant of the company Ploegsteert, in the city of Tournai. The physical and mechanical properties of the bricks were already known before the treatments were performed (Annex 1). The preparation of them was carried out in CTP (Centre Terre et Pierre), during the scheduled internship of six weeks. The bricks, however, were obtained from INISMA (INstitut Interuniversitaire des Silicates, Sols et Matériaux) which is the building and public work department of EMRA (Environment and Materials Research Association). Some first studies were performed by INISMA on the bricks behavior under the attack of the chemical compounds. For this reason, before the use of them, a cleaning process was carried out. By this way, it was possible to ensure the absence of possible contaminants, produced by previous tests, which could influence both the material's properties and the results of the investigation. Therefore, using compressed air and brushes, the bricks were restored to their initial physic state. In total, 200 kg of material was obtained from INISMA, of which 23 kilograms were used for the water absorption test and the remaining quantity for the grinding.

Figure 18: The bricks broke for the jaw crusher stage.

Subsequently, the first treatments for the crushing phase were followed. Two kinds of crushing machines were used: the jaw crusher, for the first stage, and the ball mill, for the final stage. To start the crushing procedure, the bricks were manually broken into two or more pieces to allow a better grinding process and a more efficient result from the first phase through the jaw crusher (Figure 18).

To achieve a good efficiency during the crushing phase, two jaw crushers were used to decrease gradually the granulometry in more than one step.

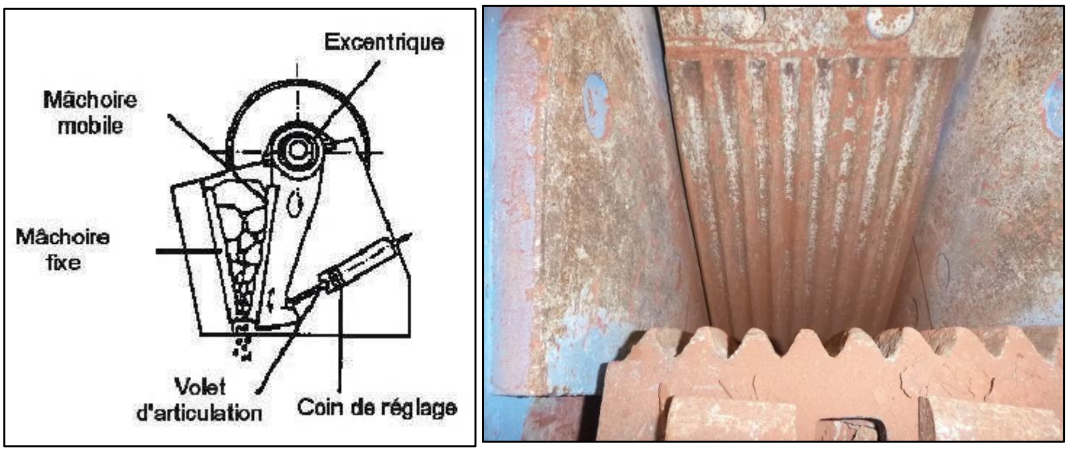


Figure 19: Scheme of the Jaw crusher (CTP, 2018), on the left, and the jaws, on the right.

The two machines used were coded, respectively, D220 and D120, by the CTP, with the specific characteristics presented in Annex 2. The jaw crusher consists of two metallic plates, defined as "jaws" and placed face to face, whose one is mobile and the other is fixed to the machine (Figure 19). The material enters inside the machine above the two plates, which start to crush and compress it until the pieces are transformed into smaller grains. The movement of the two plates guarantees both the repeated compression and the descent of the material, creating new space for the coming one. Moreover, due to the structural shape of the tool, the fed material can be crushed and fragmented several times before it reaches the target size which allows the discharge. The outcoming dimension of the particles can be modified with the change of the distance, in the lower part, between the two metallic plates. The velocity of the plates movement, together with their frequency of closing, depends on the electric motor linked to the machine.

In the first step, with the jaw crusher D220, the material to treat must have a particles size distribution between 0 and 200 mm. After the crushing, the outcoming material presents a maximum dimension of 30 mm. Due to the fragile nature of the red bricks, the treatment was rapid and with an acceptable efficiency (Figure 20).

Figure 20: Outcoming material from the D220 jaw crusher.

Then, the material was transferred to the second jaw crusher (D120) to further decrease the maximum grain size from 30 mm to 10 mm (Figure 21). In this way, the particles were crushed more easily by the following ball mill.

Figure 21: Outcoming material from the D120 jaw crusher.

After the two stages of crushing, a sieving process was performed to separate the particles under 4 mm. Indeed, this portion of material represented the brick sand fraction which was then used for the main analysis of this thesis. For this purpose, a sieve with 4 mm opening was used on the vibrating device (Figure 22). Thanks to the vibration, the particles are moved in all their faces to ensure their efficient passage through the sieve. From this stage, about 25 kg of sand, made by crushed brick, were produced. This kind of sand was produced to achieve the same physical properties of the limestone natural sand, usually used in the self-compacting mortar composition.

The remaining part, with a dimension above the 4 mm, was then transferred to the ball mill. The grinding step was performed to guarantee the reduction of granulometry and the production of the second sample material, the brick filler.

Figure 22: Sieve employed for the separation of the fraction under the 4 mm of dimension.

The objective, in this case, was to achieve a particles size distribution as much as possible like the limestone filler, which is typically used to produce self-compacting mortar.

The ball mill consists in a rotating mill that contains a specific amount of balls (70 kg) (Figure 23). They can be made by a different kind of material, depending on the type of sample, which must be treated. Furthermore, also the diameters can be changed according to the kind of grinding process which is planned. As for the jaw crushers, the frequency of the rotation depends on an electric motor directly connected to it. Thanks to the rotation of the mill, the balls inside start to move and the materials between them start to be ground.

Different parameters must be adjusted before the obtaining a satisfactory result, in terms of physical characteristics. The main parameters are the balls features and the duration of the process. In this case, the balls made by stainless steel were chosen with a diameter between 25 and 30 mm.

Figure 23: The ball mill outside, on the left, and inside, on the right.

The crushed red bricks coming from the jaw crushers were divided in samples of 15 kg each. In this way, the addition of the balls together with the materials did not overpass the capacity limit of the mill equal to 65 liters, leading to a good grinding efficiency. Moreover, the duration of the process was monitored to achieve the prefixed granulometry of the material. For this reason, during the process, different steps are performed for intervals of 10 minutes.

After each time interval, a sieving analysis was performed to check and verify the particles size distribution of the brick filler and to guarantee the granulometric similarity with the particles size distribution of the limestone filler used for this work. In this specific case, the sieving test was conducted through the Alpine Air jet sieving, in which, thanks to the creation of the vacuum in a chamber, the material was sieved. The granulometric analysis was performed respectively with the sieves of 25 μm, 45 μm, and 90 μm of opening and an interval of ten minutes. At each interval of time, in order to pick up the most representative sample of brick filler, a multi-level sampling rod was used (Figure 24).

Figure 24: The rod used for the material sampling.

The material for the sieving test was weighed to have a sample of 5 g to be then treated through the device. The quantity of material must be in a considerable quantity to avoid an overload of the sieves and, as a result, an inefficient process with more time-consuming. After the ten minutes stage, the material refused by the sieve was weighed to ensure that its quantity is under 30 % (for the 25 μm sieve) and 10% (for the 45 μm and 90 μm sieves) of the initial sample's weight. After two stages of ten minutes performed through the ball mill, the satisfactory results were obtained for the material's granulometry. All the processes performed for the preparation and the treatments of the brick sand and the brick filler are summarized in Annex 3: Flowsheet for the bricks treatment

4.1.2 Characterization methods

After the preparation of the waste red bricks, the characterization of the filler and the sand material was the next step. While, for what concerns the traditional constituents for the self-compacting mortar, like the Portland CEM I 52.5 N, the limestone sand and the limestone filler, it was possible to take the characterization results from the literature of a previous research[1]. Through the results coming from the characterization tests, the comparison between the filler and the sand made of the red waste bricks, as recycled materials, and of the limestone, as traditional material, was conducted.

[1] By Mohamed Elkarim Bouarroudj, Ph.D student at the University of Liège, in 2017.

The volumetric mass analysis

The first analysis conducted on the recycled materials and on the traditional ones regarded the volumetric mass. According to the granulometry of the materials, the test was performed through different devices. In the case of the filler constituents, as the brick and limestone fillers, the density was investigated through the glass and the helium pycnometers. While considering the sand fraction of the self-compacting mortar, the investigation was conducted through the stainless-steel pycnometers, according to the European standard EN 1097-6.

The volumetric mass analysis through the pycnometers is an indirect method. Indeed, the volume is computed through the pycnometer weights in several conditions. The first is in empty conditions without any material. The second is with the addition of the water inside. While the third, is the weight of the pycnometers filled both by the water and the material. Both the stainless-steel and glass pycnometers have a tight-fitting stopper characterized by a tiny hole in the center. During the measurement of the weight the role of this hole is important. It permits the escape of the water in excess maintaining the volume constant. The positioning of the stopper and the weight measurements are usually performed after 24 hours of stable conditions for the pycnometers. This precaution permits to avoid the dispersion of possible material still in suspension in the water phase.

For the brick filler case, the helium pycnometer was used to determine the true volume and the absolute density of the material. The volume is computed by the drop pressure, which is originated when a known quantity of gas can expand in a chamber containing the filler sample. Therefore, the volume computed by the helium pycnometer does not consider the pores, which are not accessible to the gas. The choice of the helium, as gas for the measurement, is due to its condition of ideal behavior. The measurement, furthermore, allowed a high-speed, with a high precision, measurement of the volume and the density of the filler.

Regarding the glass pycnometer, it also permits the absolute density determination, with a still satisfactory precision, of a solid material which does not dissolve in the working liquid, represented generally by the distilled water (Figure 25).

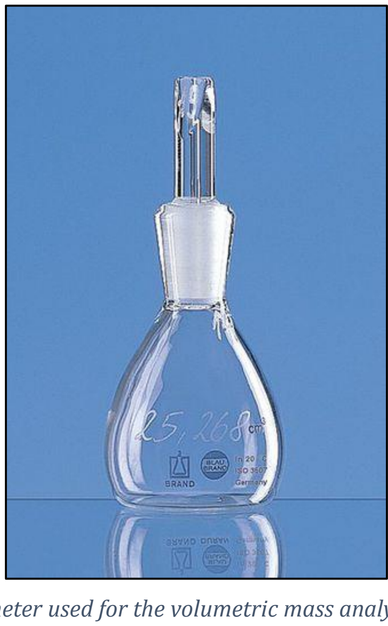


Figure 25: The glass pycnometer used for the volumetric mass analysis on the brick powder [75].

Generally, to have enough result guaranteeing a representative value, the test is performed at least on three pycnometers. The first step is to measure the weights of the empty pycnometers.

Then, the pycnometers filled by only water are weighed. In the end, the pycnometers are filled by the sample, the brick filler in this case, and the distilled water and they are weighed. The three pycnometers are left on a stable base for 24 hours to guarantee the deposition of the possible grains still in suspension in the water phase. The pycnometers, after the 24 hours, are closed with the stoppers to ensure the outflow of the distilled water in excess. In the end, the closed pycnometers, filled both by the solid material and by the distilled water, are weighed.

The mass and the volume of the solid material is then computed through the following formulas.

$$M_{brick\ powder} = M_{p+b} - M_p$$

$$V_{brick\ powder} = \frac{(M_{p+w} - M_p) - (M_{p+b+w} - M_{p+b})}{\rho_w}$$

$$\rho_{brick\ powder} = \frac{M_{brick\ powder}}{V_{brick\ powder}}$$

$\boldsymbol{M_{p+w}}$	Mass of the pycnometer with water
$\boldsymbol{M_p}$	Mass of the pycnometer
$\boldsymbol{M_{p+b+w}}$	Mass of the pycnometer filled with water and solid material
$\boldsymbol{M_{p+b}}$	Mass of the pycnometer filled with the solid material
$\boldsymbol{\rho_w}$	Density of the water at 25°C
$\boldsymbol{\rho_{brick\ powder}}$	Absolute density of the brick powder

For the coarser fraction, as in our case the brick sand with the granulometry between 0 and 4 mm, the glass pycnometers is not suitable to achieve a good accuracy in the density measurement. For this reason, usually, it is used the stainless-steel pycnometer (Figure 26). As for the glass pycnometers, the absolute density measurement is performed on at least three pycnometers to achieve a representative result. The same procedure seen for the glass pycnometers is followed also with the stainless-steel pycnometers.

Figure 26: The stainless-steel pycnometer used for the volumetric mass analysis on the brick sand.

The water absorption analysis

Zhao et al. investigated the influence of the hardened cement paste on the water absorption of fine recycled concrete aggregates. In particular, the water absorption test was carried out both following the European Standard NF EN 1097-6 [76] and the IFSTTAR n°78 method [62]. With the results of the analysis, they demonstrated the possibility to use these two methods to obtain the water absorption coefficient from the saturated surface dry state. However, the two approaches do not measure in a accurate way this coefficient, underestimating and overestimating the final value. For this reason, the research was concentrated on the development of a linear extrapolation method referring to the results of the water absorption on material with different granulometry.

In the case of the sand and the filler made from bricks, the presence of fine particles can lead to the cohesion between them, influencing the final water absorbed value. Indeed, due to the capillary forces presented between particles, the water can be trapped, increasing in this way the agglomeration and influencing the results of the tests.

Figure 27: Steel cone and pestle for the NF EN1097-6 test.

However, in this case study the water absorption analysis was performed on two materials coming from the treatment of the waste red bricks: the brick sand (with a granulometry between 0 and 4 mm) and the coarser brick pieces (with a granulometry over the 4 mm of diameter).

First, the materials were totally immersed in the water for 24 hours to reach the complete saturation. Then, they are dried following two different ways: the standard method (according to the European standard EN 1097-6) and the IFSTTAR method.

The standard method consists in the drying phase of the material through a gentle current of warm air which allows the evaporation of the water between and on the surface of the particles. The second stage is the evaluation of the slump on the sample, after fixed time intervals, where it is possible to notice the cohesion between the grains. The material is introduced and gently pressed in a steel truncated cone to fill all the space (Figure 27).

After the lifting of the steel truncated cone, the shape of the material cone is evaluated to identify the grade of the saturated surface dry state. If the cone of material presents a shape different from the one displayed by the Figure 28, the drying process continues for another fixed interval of time. Instead, if the shape of the cone corresponds to the Figure 28, the material is weighed and, then, left in the oven for 24 hours at 105°C, until the grains reach completely the dry state. After the drying stage, the sample is weighed again, and the water absorption coefficient is computed through the formula shown subsequently.

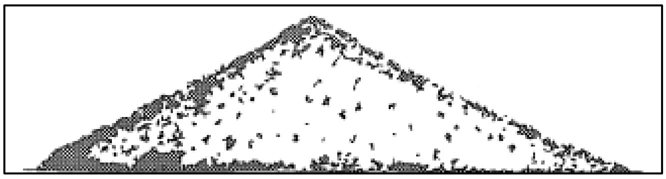


Figure 28: Shape of the sand cone at the saturated dry surface stage for the norm EN1097-6.

Due to the procedures imposed by the European Standard EN 1097-6 and to the more extended drying phase, the method underestimates the final water absorption of the material.

Also during the IFSTTAR method is possible to face some agglomeration phenomena between the particles. Indeed, the procedure consists in the drying phase of the material through simple colored paper until the saturated surface dry state is reached. However, the use of this paper does not guarantee a good separation of the particles, leading to the overestimation of the final water absorbed. The water, in fact, is present both inside the grain's pores and between the different particles, in the form of interstitial water. The material, after the manual drying phase, in both two methods, is weighed and placed inside the oven at 105°C until it is completely dry. Then, the bricks are weighed again, after the oven stage, to compute the final water absorption coefficient (W_{A24h}), as displayed in the following formula.

$$W_{A24h} = \frac{(M_d - M_w)}{M_d}$$

M_d	Dry mass of the material (g)
M_w	Wet mass of the material (g)

In this work only the IFSTTAR method was performed due to the more underestimation of the value by the standard method which did not allowed a suitable computation.

β-p test

Usually, the binder's constituents, like in this case the brick filler, and their proportion in the mixes, are evaluated according to the requirements imposed for fresh and hardened properties of the mortar. However, the large number of combinations inside the mixes can affect the time needed for the test. For this reason, it is suggested to perform a preliminary test [77]. *Okamura et al.* used a simple flow spread test, like the slump test for the concrete, for the evaluation of the binder proportions in the production of the self-compacting concrete and mortar. The test consists of a truncated cone shape mold (Figure 29) filled by the paste, in two layers, and placed on a glass plate. Each of the layers is compacted 15 times with a steel rod. Then, the mold is lifted and the spread is measured, by means of its diameters, to obtain a mean value between 140 mm and 280 mm. The procedures are then repeated for other proportions of the material and of the water, until the enough points are reached to display the linear relation of the Figure 30.

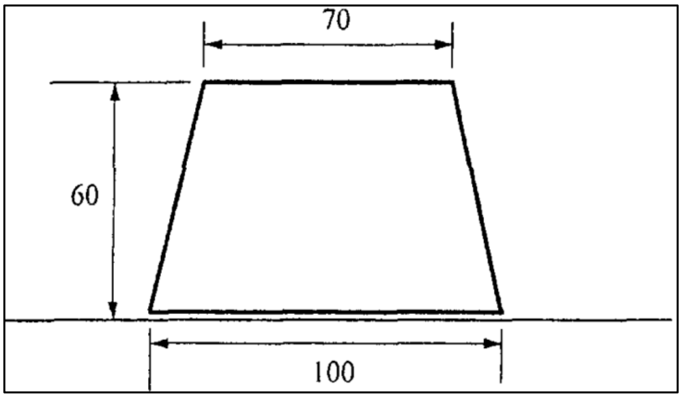


Figure 29: Dimensions of the mold used for the test [77].

Then, through the measurements of the average diameters (D) of the spread, the relative flow area (R) is computed with the following formula.

$$R = \frac{(D^2 - 100^2)}{100^2} = \frac{D}{100^2} - 1$$

Okamura et al., furthermore, investigated the relationship between the relative flow area and the water to powder ratio (V_W/V_P), demonstrating the linear dependency of them (Figure 30).

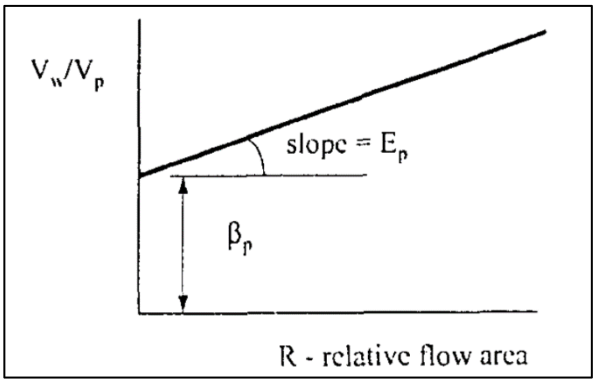


Figure 30: Linear relation between the relative flow area and the water-powder ratio [77].

The ratio between the water and powder is computed through the following formula, in which there is a clear dependency with the relative flow area (R).

$$V_W/_{V_P} = \beta_P + R * E_P$$

The β_p represents the water ratio, which considers the water inside the pores of the material's particles and the interstitial one between the grains. So, it represents the quantity of water needed to achieve a good slump spread for different ratio of water-powder. While the E_P, defined as the deformation coefficient, describes the sensitivity of the paste's fluidity with the variation of water content.

Thanks to the results obtained for the brick filler pastes, the behavior between the material and the water was studied and evaluated before the design of the self-compacting mortar.

Vicat test

To ensure the reaching of the standard consistency for a paste, in this case, made by the water and the brick filler, a specific amount of resistance to the penetration by a standard plunger must be determined. This consistence can be reached by a specific quantity of water inside the paste. In order to discover this value, trails of penetrations in the paste are performed with different amounts of water [78].

The apparatus for the Vicat test (Figure 31) is composed by a right cylinder-shaped plunger usually made of a stainless steel, with known weight and dimensions, and by the truncated conical shaped mold, in hard rubber, on the plastic base-plate.

Figure 31: The apparatus for the Vicat test.

The quantity of material used for each trial is every time 500 g, while the water is changed until the pre-fixed result is achieved. The first step, after the calibration of the apparatus, is the mixing between the material and the water. The mixer is started at low speed for 90 s. After the interval of time, the paste which possibly had adhered to the bowl wall, far from the mixing zone, is removed and the mix is restarted at low speed for 90 s.

The paste produced must be transferred immediately into the mold, until it is filled to excess. Then the excess is gently removed, and the mold is centrally positioned under the plunger. The plunger is immediately lowered gently to be in contact with the paste. Then, the moving part is released to penetrate the paste. After 30 seconds of penetration, the height on the scale, which indicates the distance between the bottom of the plunger and the base plate, is recorded.

The test is repeated for pastes with different amount of water content until a height of 6 mm is recorded on the plunger scale. The paste that presents this characteristic, has the right water content for the standard consistence [79].

Thanks to the optimal ratio between the water and the powder material, is possible to compute the real compactness (Φ) of the mix skeleton through the following formula:

$$\Phi = \frac{1}{1 + \rho_p * \frac{w}{p}}$$

$\boldsymbol{\rho_p}$	Real density of the powder (g/cm³)
$\boldsymbol{w/p}$	Water-powder ratio (-)

The real compactness of a sample represents the quantity of material presents inside a given volume, considering the air presence. Usually, the higher is the real compactness, the higher is the quantities of material particles and the lower is the air present.

Specific surface analysis

In order to study the fineness of the filler fraction, in this case, made by red waste bricks, the analysis on the specific surface is performed through the Blaine method, according to the European Standard EN 196-6. The final value is expressed as the total surface area of the sample in a precise weight value. The higher this parameter is, the finer is the filler analyzed. The Blaine method consists in the principle of the air permeability through the sample.

Figure 32: The container used for the Blaine test for the specific surface area [80].

The procedure consists in measuring the time needed for air to flow through a precise quantity of material, with defined porosity, compacted inside a container with a known volume (Figure 32). First, a perforated disc and a paper filter are placed in the bottom of the container to allow the better flowability of the air.

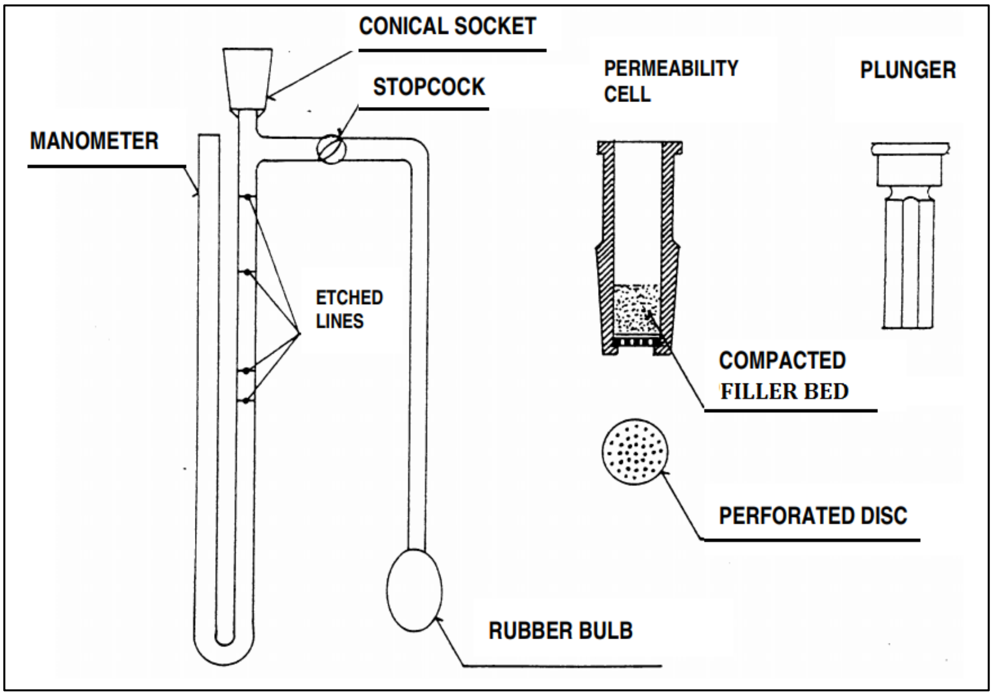


Figure 33: The scheme of the Blaine apparatus used for the specific surface analysis [79].

Then, the container is filled by the known quantity of sample and a second paper filter is placed on it. The plunger is inserted and pressed until the lower part of the cap is in contact with the cell.

Now, the bed of material is well compacted and ready for the analysis of the test. The Blaine apparatus, a manometer with a U-tube shape, is used for the test (Figure 33).

One arm of the manometer is composed, at the top, by a conical socket to ensure the airtight fit with the cell. The same arm is linked, through a T-shaped joint, with the second arm where an air stopcock guarantees or stops. the flow of the air. Attached to this arm, a rubber bulb provides the aspiration of the air into the device. The manometer is filled with a non-volatile, non-hygroscopic liquid with low density and viscosity [79].

The first step is to insert the conical cell into the conical socket until they fit perfectly. Then, the stopcock is opened, and, through the rubber bulb, a gentle aspiration of air raises the level of the liquid inside the manometer to the highest fixed line. The stopcock is then closed, and the liquid will start to decrease its level. The time starts to be recorded when the liquid reaches the second line and it is stopped as the liquid achieves the third printed line [79].

Finally, knowing the time interval, the physical properties of the material and the experimental conditions is possible to compute the value of the specific surface area through the following formula.

$$\boldsymbol{S} = \frac{\boldsymbol{K}}{\boldsymbol{\rho}} * \frac{\sqrt{\boldsymbol{e}^3}}{(\boldsymbol{1}-\boldsymbol{e})} * \frac{\sqrt{\boldsymbol{t}}}{\sqrt{\boldsymbol{10}\,\boldsymbol{\eta}}}$$

S	Specific surface [cm^2/g]
K	Constant of the device
$\boldsymbol{\rho}$	Volumetric mass density of the material [g/cm^3]
e	Porosity of the material
t	Average of the time interval recorded [s]
$\boldsymbol{\eta}$	Air viscosity for the sample temperature [Pa*s]

This procedure is performed for three times on the same sample. The final specific surface value is then obtained by the mean of the three tests results, guaranteeing, in this way, the best representative value.

Granulometric analysis

According to the granulometry range of the material which must be studied, the particles size distribution can be measured through different methods. In the case of the fillers, due to its fineness, the best and suitable way to analyze its granulometry is through the laser diffraction. While for the sand fraction, the vibratory sieving is preferred for the separation in the different range of granulometry.

The test is performed especially on the brick sand and the brick filler. The aim is to compare the granulometric distribution between the red waste bricks samples (filler and sand) to the traditional limestone constituents (filler and sand). Concerning the limestone constituents, the granulometric curve is taken from the literature of a previous research[2].

[2] By Mohamed Elkarim Bouarroudj, Ph.D student at the University of Liège, in 2017.

The device used for the analysis of the filler, in this specific case study, is the Malvern Mastersizer 2000, with a range of detection between 0.02 and 2000 µm (Figure 34).

Figure 34: Laser diffraction spectrometer Malvern Mastersizer 2000 [81].

After a calibration step for the device, the specimen is dispersed, using sodium pyrophosphate and the ultrasound tank, to ensure the best measurement with the right state of dispersion and avoiding possible agglomeration phenomena. The system measures the intensity of the laser beam diffraction through the dispersed material. The detectors in the chamber evaluate the intensity over a wide range of angles (Figure). The software, linked to the spectrometer, checks the measurement procedure and compute the particles size distribution according to the scattered data.

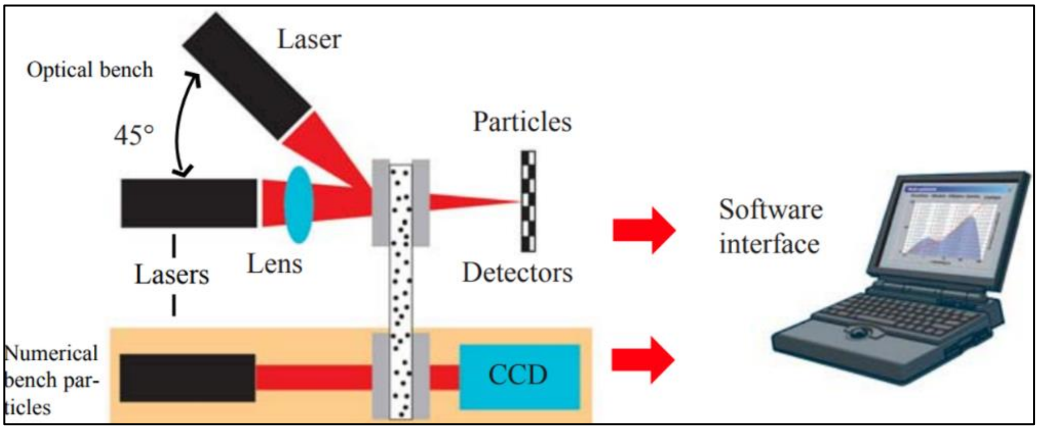


Figure 35: The measurement process by the laser diffraction spectrometer[82].

It must be mentioned, however, the importance of the sample quantity introduced into the device before the measure starts. Indeed, if the amount of the sample inside the ultrasound tank is too large, the obscuration can increase. The obscuration can be defined as the light percentage which can be attenuated by the diffusion and the adsorption by the particles. So, according to its changes and its influence on the two laser sources, the amount of sample has to be adjusted to achieve an accurate measurement. On the other hand, if the quantity of the sample is too low, the number of particles in the medium will not guarantee a satisfactory analysis of the particles size distribution.

To further check the particles size distribution of the brick filler, another granulometric analysis was conducted, through the laser diffraction spectrometer CILAS 1180L (Figure 36), during the internship at CTP.

Figure 36: Particles size analyzer CILAS 1180L [83].

However, for the granulometric analysis on the brick sand, the vibratory sieve shaker AS200 by RETSCH was used (Figure 37). The test is performed on three samples, made by 300 g of material each, to ensure the representative result of the particles size distribution. The sieving is performed for ten minutes with an amplitude of 40% to guarantee a good separation of the particles between the several sieves.

Figure 37: the vibratory sieve shaker AS200 by RETSCH.

After the ten minutes stage, the material remained in each sieve is recovered and weighed. In this way, is computed the percentage, that it represents, respect to the total weight of the tested specimen. With all the percentages obtained for each sieve, the granulometric curve can be depicted.

GranuHeap

Usually, when a powder is spread on a surface, it forms a heap. The heap characteristics, such as the friction angle and its shape, are strongly dependent on the properties of the grains' material. The cohesiveness has the most influence on the shape of the heap: the material with a higher cohesiveness presents an irregular shape of the heap, while, in the case of low cohesiveness the powder is made of a regular heap.

The study on the heap shape, with precise devices, can provide important results for the analysis of the physical characteristics for a powder material. To ensure the representative results on the heap shape, avoiding any influence of the formation method, an automated initialization is necessary together with a precise measurement technique.

Lumay et al. [..] studied the physical properties and, in this case, the cohesiveness of powder materials by the analysis through the GranuHeap instrument. It's an automated device based on the measurement of the heap shape through the image processing. The device is composed of a cylindrical support, where the heap is formed, and an initialization tube which has the internal diameter equal to the support. The tube is installed on the support and, then, filled with the material until a fixed volume is reached. Subsequently, the tube starts to be lifted with a constant speed of 5 mm/s. The material starts to flow from the tube to the cylindrical support to form a heap. The support is rotated automatically to obtain different heap projections and orientation. The number of images and the interval of rotation depend on the study and the heap shape. For each image, the software measures the repose angle (α_r)(Figure 38), which is the approximated angle of the isosceles triangle with the most similar shape of the heap image. In the end, an average value of all the friction angles is obtained. The deviation between the isosceles triangle and the real heap shape produces the static cohesive index σ_r. The value is computed for each image and an average result is obtained. The closer to zero the friction angle is, the more the powder presents a non-cohesive behavior. The increase of it happens when the cohesive forces inside the powder material are stronger.

Moreover, the study of *Lumay et al.* shows the influence of the grains size and their distribution on the repose angle (α_r). The results on the samples with different distributions of granulometry presented the increase of the repose angle with the decrease of the grains' dimensions. This can be linked to the presence of the higher cohesive forces between the particles which allow the formation of a heap with a steeper angle

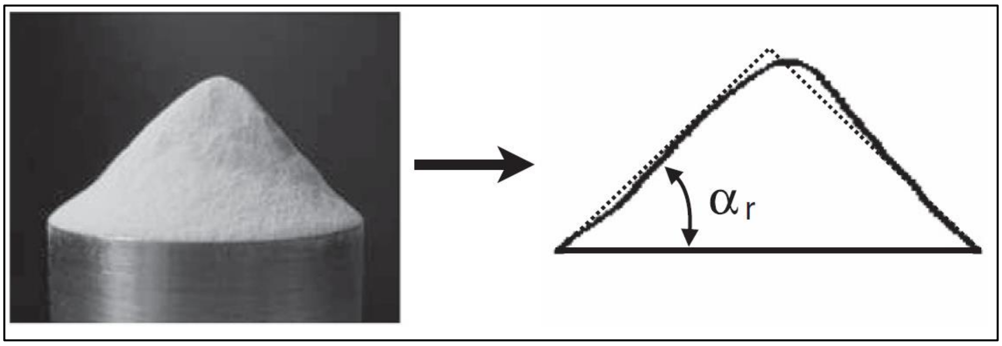


Figure 38: The cylindrical support and the computation of the repose angle α_r [84].

This type of test is conducted both for the Portland CEM I 52.5 N and for the filler materials used in this study, made of bricks and limestone, to compare the cohesiveness of the samples. Thanks to results is possible to understand in which material the smaller particles have a greater influence on the cohesiveness [84].

GranuDrum

To study the flow of granular and powder material, in the most practical and simple way, the GranuDrum analysis represents the most suitable choice. The apparatus is composed of a horizontal aluminum cylinder with the walls made of glass. The powder material is introduced inside until the cylinder is half-filled. Then the device starts to rotate on his axis with a fixed angular velocity (Ω), inducing the flow of the material. During the rotation, the cylinder is backlighted and recorded with a CCD camera. The test is performed with different values of angular velocity. For each of them, the camera obtains 50 images with an interval of 0.5 s (Figure 39).

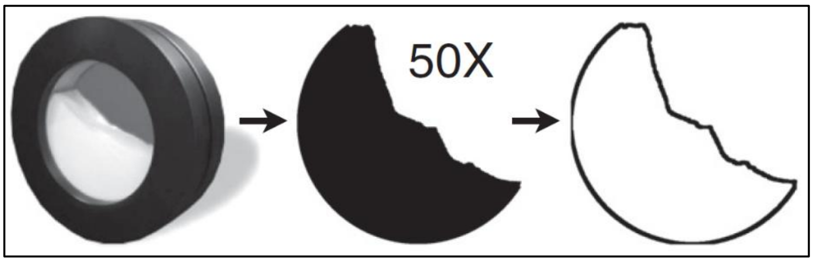


Figure 39: Shape of the aluminum cylinder with the sketches of the GranuDrum measurements [84].

By the photos taken, the material is identified by the black color, while the remaining air, inside the cylinder, by the white color. Through an edge detection, the position of the interface between the air and the material is detected. Then, the average position and the dynamic cohesive index (σ_f) of it are computed. Thanks to the analysis on this parameter, the cohesiveness of the powder can be studied. Indeed, a non-cohesive material, at a given angular velocity (Ω), shows a continuous flow. During the rotation of the cylinder, the flowing angle (α_f) is computed, in the center of the flow, starting from the average interface position.

In general, if the powder presents a low value of flowing angle, it presentes also a good flowability. Nevertheless, the flowing angle is a parameter which depends on the friction between the grains, the shape of the particles and the cohesive forces between them. To study the cohesive forces which act inside the structure of the powder material, the dynamic cohesive index must be analyzed. The powder materials which present an intermitted flow during the GranuDrum test can be classified as cohesive materials. While, if the flow is regular, the material can be considered as non-cohesive. So, if the dynamic cohesive index increases, it means that the cohesiveness of the material increases. On the other hand, the decreasing of the index corresponds to a less cohesive material.

Both the flowing angle and the cohesive index are linked to the grains size of the powder material [84]. Lu*may et al.* have studied, as for the GranuHeap analysis, the influence of the particles size on the flowing ability of the materials. When the grains size starts to become lower than 50 μm, the cohesion begins to cover an important role. If the size is above 50 μm, the cohesion can be considered as negligible. Moreover, the role of the size distribution was analyzed. The results demonstrated that the increase of the size for d(0.1) led to more flowability for the material. On the other hand, with a decreasing size for the smallest particles inside the distribution, the material starts to present more cohesion and the flowing angle becomes larger. In the end, also the influence of the elongation of the grains material was studied on the GranuDrum test.

In this case study, the Portland CEM I 52.5 N and the brick filler are tested through the GranuDrum to further investigate the cohesiveness of the materials already checked in the GranuHeap test.

GranuPaq

The bulk density together with the tapped density and the Hausner ratio (Hr) are parameters which can be measured in the simpler and rapid way. The most reliable and efficient way to measures these physical properties is through the GranuPaq instrument. It's an automated device which permits the measurement of the tapped density through improved techniques [84].

The test consists in the introduction of the powder material, with a fixed mass, inside a 250 ml glass cylinder (Figure 40). The initial volume (V0) is measured by naked eyes, and, then, the pile is treated with 500 calibrated taps. One tap corresponds to a free fall of the cylinder over a fixed distance Z. After each tap, the height of the material is recorded. In the end, the final volume (Vf) is recorded. Then, the Hausner ratio is computed through the ratio between the final and the initial volume of material inside the glass container.

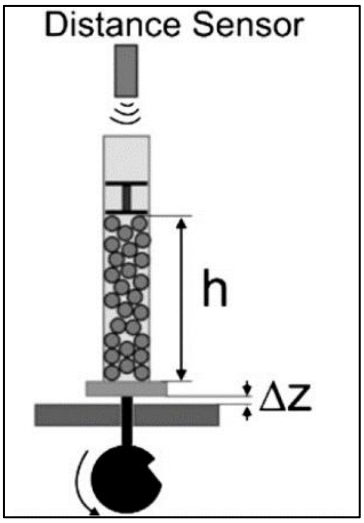


Figure 40: Scheme of the GranuPaq device measurement [84].

The test presents three main drawbacks. First, the initial volume measurement by naked eyes is extremely subjective. Indeed, the method of measure and its results depend on the operator which is performing the test. Secondly, the filling procedure is also influenced by the operator which can affect the initial volume V0. The third is represented by the lack of information about the compaction dynamics between the initial and final volume measured [84].

Knowing the mass of material introduced inside the device, it is possible to compute the bulk density as a function of the taps number, with the initial $\rho[0]$ and final $\rho[500]$ value. Furthermore, during the test are computed the number of taps to reach the half of the final packing density ($n_{1/2}$) and the maximum packing density reachable (ρ_∞).

As for the GranuHeap and the GranuDrum tests, *Lumay et al.* studied the influence of the grains shape, their distribution and their size on the packing density. From the study, it was demonstrated the increase of the initial and final packing density when the particles were under 50 μm diameter, while for particles above the packing density becomes lower. The Hausner ratio, due to its relationship with the two packing densities, follows the same trend. Concerning the $n_{1/2}$ parameter, its decrease is expected for the particles with a lower dimension (d< 50 μm) due to the cohesive forces' role during the test. In the case of larger particles, the parameter starts to increase due to the need for more energy to move a grain with higher dimension and higher mass. Furthermore, the increase of the grains dimension leads to a wall effect more considerable during the test, leading to the further increment of the $n_{1/2}$ parameter. The distribution of the particles covers another impotent role: considering the *d(0.1)* of the material, with the decreasing of the diameter, the Hausner ratio and the $n_{1/2}$ presents larger values.

Considering the elongation of the particles, when they show a longer shape, the packing density begins to decrease, due to the voids still present between the grains and the lower mobility of the grains. This tendency leads to a lower compaction characteristics' value.

5. Characterization Results

Before starting the investigation on the final mortar samples, the first stage consisted in the characterization tests both on the natural material (cement, natural sand, limestone sand and limestone filler) and on recycled products (brick's filler, BP, and brick's sand, BS). Indeed, the knowledge of the physical and chemical characteristics of the material represents the main step to achieve a good comprehension of the behavior of the mortars. The characterization process was conducted in collaboration with Mr. Mohamed El Karim Bouarroudj, a Ph.D. student at the University of Liège in the Laboratory of Building Materials.

5.1 Cement

For the analysis on the self-compacting mortar, a Portland CEM I 52,5 N was used: it contains 97% clinker and 3% filler (Annex 4). From the technical information given by the producer, the absolute density is given (Table 5).

Absolute density [kg/m^3]	3100

Table 5: The absolute density of the Portland CEM I 52,5 N.

For what concerns the analysis on the consistency of the cement paste, the water demand is measured, according to the norm EN 196-2 [78]. This parameter is defined as the quantity of water which must be added to 500 g of a filler material, to reach a sinking of the Vicat probe equal to 6 mm ().

Water mass added to reach the probe sinking of 6 mm for the Vicat test (g)	169.60

Table 6: The quantity of water recorded through the Vicat test.

As for the test on the consistency of the paste (material together with water), the value of the compacity is determined through the Vicat test according to the European Standard EN 196-1.

The parameters used for the computation of the real compactness for the cement are depicted in Table 7.

M_v	Absolute density [kg/cm^3]	3100
M_e	Water mass added to reach the plunger sinking of 6 mm for the Vicat test [g]	169.60
M_p	Filler mass for the test [g]	500

Table 7: Cement parameters for the compactness computation.

Finally, the compacity of the Portland CEM I 52,5 is depicted in Table 8.

C	Compacity [-]	0.49

Table 8: Compacity of the Portland CEM I 52.5.

The compacity represents the quantity of material inside a given value of volume, considering the presence of air. The Usually, the higher the compactness is, the higher the mechanical properties of the final product are.

5.2 Limestone filler

The limestone filler used for the production of the self-compacting mortar is CALCITEC 2001S: the physical and chemical characteristics are depicted on the technical sheet (Annex 5).

Volumetric mass

The volumetric mass, in this case real density, of the limestone filler is analyzed for using it in the computation of the other physical parameters. In this case, the measure is performed by means of the gas pycnometer (Table 9).

Real density [kg/m^3]	2734

Table 9: The absolute density of the limestone filler.

In the technical sheet, a value of 2700 kg/cm^3 is mentioned, which is not so far from the experimental result.

Granulometry

The first test performed on the material was the particles size distribution. The curve was obtained in humid condition through the laser diffraction (Figure 41). The trend shows the good uniformity of the particles size distribution without a monodisperse behavior.

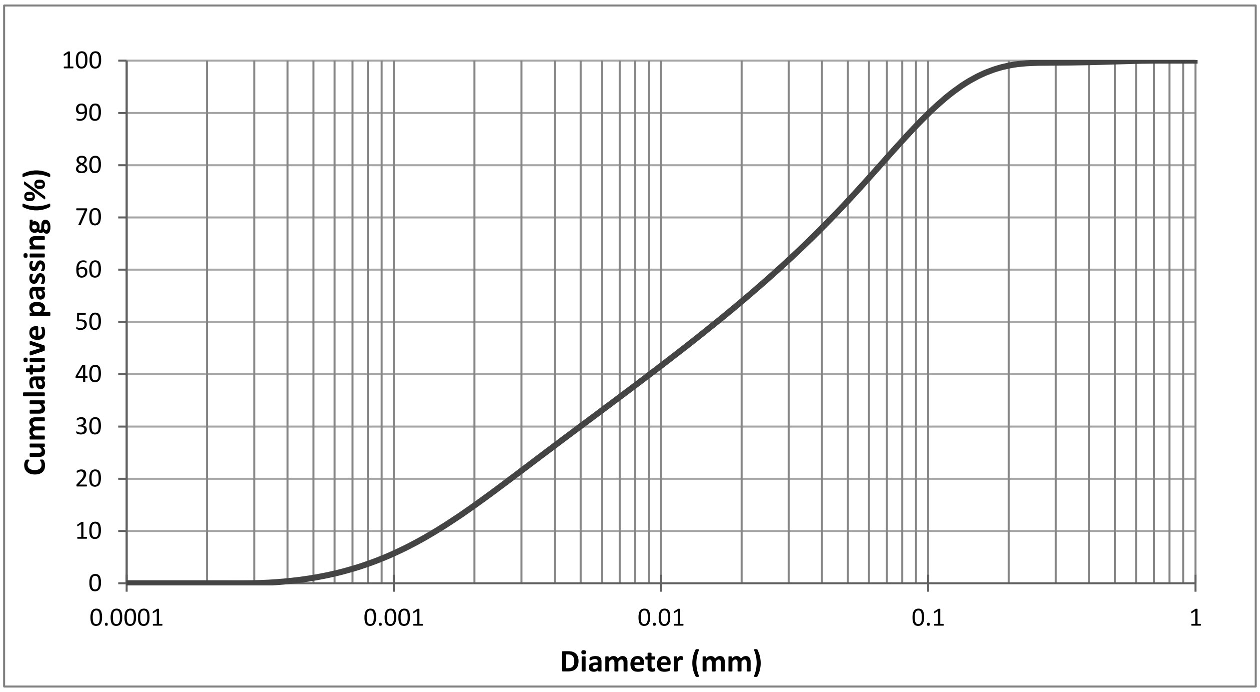


Figure 41, Particles size distribution of the limestone filler.

Specific surface (Blaine test)

As for the cement fraction, the limestone filler is treated through the Blaine test, to measure the specific surface area. However, the parameters can present different values, according to the material as shown in the Table 10.

K	Constant of the device	24.9
$\boldsymbol{\rho}$	Volumetric mass density of the material [g/cm^3]	2.73
e	Porosity of the material [-]	0.05
t	Average of the time interval recorded [s]	44
$\boldsymbol{\eta}$	Air viscosity for the sample temperature [Pa*s] (20 °C)	0.00001824

Table 10: The parameters used for the specific surface analysis through the Blaine test.

Even if the specific surface area was already displayed in the technical sheet, with a value equal to 3550 cm^2/g, a second measure was performed to guarantee a more precise characterization of the material. The final specific surface recorded by the test was 3174.88 cm^2/g, resulting in a lower value than the one provided by the company CARMEUSE.

5.3 Limestone sand

A 0/4 mm limestone sand was used in the substitution analysis of the sand component by the brick sand. In this case, Carmeuse in Engis provided the material. The tests for the characterization and the investigation of the physical properties3 were performed.

Volumetric mass

The absolute and real volumetric mass was computed using the steel pycnometers leading to the following results (Table 11).

Absolute volumetric mass (kg/m3)	2645
Real volumetric mass (kg/m3)	2590

Table 11: Absolute and real density for the limestone sand.

Granulometry

Then, the granulometry analysis was performed to investigate the particles size distribution of the material (Figure 42). The test was performed through the vibratory sieve shaker, after the drying stage of the material.

[3] By Simone Delvoie, researcher at the University of Liège, in 2018.

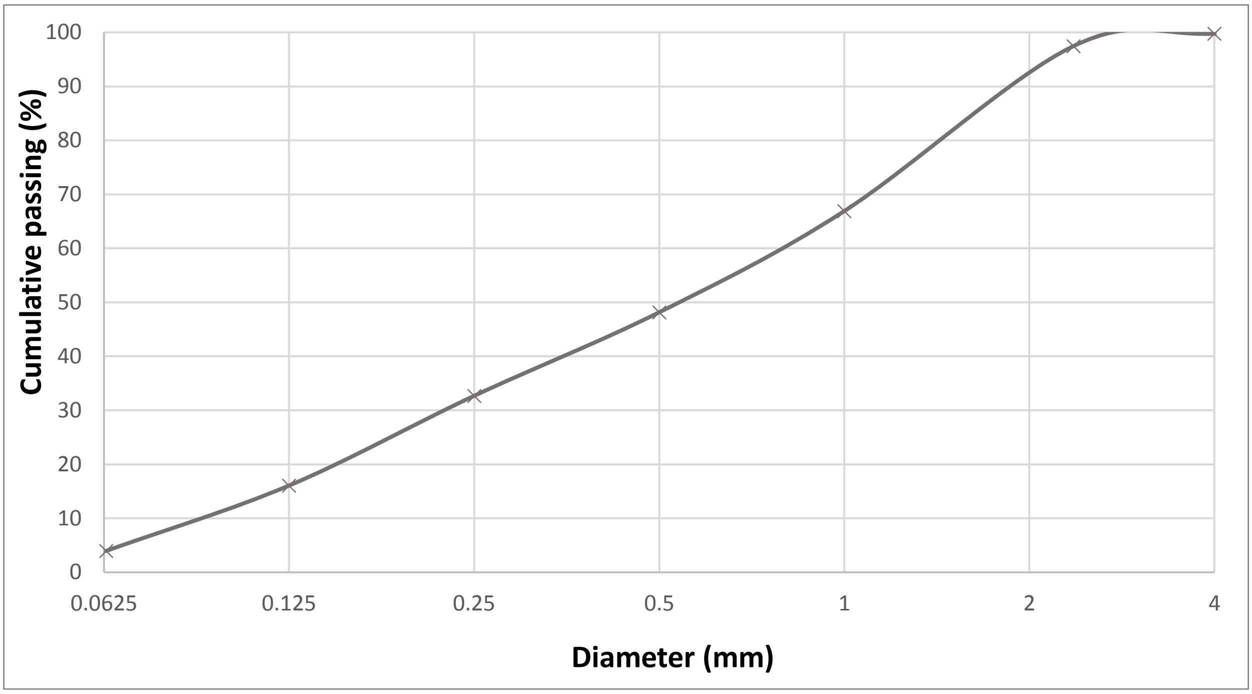


Figure 42: Particle size distribution for the limestone sand.

Water absorption analysis

Water absorption was also measured on the limestone sand. For this analysis, the method used is referred to the European Standard EN 1097-6, which defines the method for sandy material with a granulometry between 0 and 4 mm. The final water absorption coefficient measured is displayed in Table 12.

W_{A24h}	Water absorption coefficient (%)	0,84

Table 12: Water absorption coefficient for the limestone sand.

5.4 The normalized sand (EN 196-1)

During the production of the mortar samples with the limestone filler replacement by the brick's filler, a normalized sand, conform to the European standard EN196-1, is used. The material comes from the Société Nouvelle du Littoral in Leucate (France). The material was characterized through several tests to determine the physical properties. The volumetric mass was analyzed, according to the European standard EN 1097-6, through the measurement by the pycnometers. The same European norm was followed for the water absorption analysis to determine the related coefficient. While, the granulometric analysis was performed through the vibrating sieving, usually used for sandy materials. The physical properties are depicted in the technical document provided by the company (Annex 7).

The use of this sand for the analysis on the limestone filler substitution, is due to its specific physical features. Thanks to the low water absorption coefficient, the behavior of the paste can be studied easily. In this way, the only interaction of the water is with the filler constituents and the cement fraction.

5.5 The recycled materials

The recycled materials used as a substitution for the filler and sand constituents are:

- The brick sand, with a range of granulometry between 0 and 4 mm, created through the crushing process of the two jaw crushers (see Chapter 3);
- Bricks' filler, with a granulometry under 100 µm, produced by the crushing and grinding process conducted with the jaw crushers and the ball mill;

The mineralogy and the chemical composition of the material were studied4 on a portion of material taken from CTP. In the laboratories of INISMa, the analysis was conducted through the x-ray diffractometer RIGAKU MiniFlex 600 (Figure 43).

Figure 43: Rikagu MiniFlex 600 for the mineralogical and chemical analysis (Rigaku, 2018).

First, through the software Crystal, the different mineralogical phases were detected, computing their mass percentage, together with the quantity of amorphous phase (Table 13).

Mineralogical Compound	Content (%)
a-SiO_2/Quartz Alpha	**53.3**
a-Fe_2O_3/Hematite	**10.8**
KAlSi3O8/Microcline Intermediate	**9.2**
NaAlSi3O8/Albite	4.0
SiO2/cristobalite	2.7
Amorphous phase	20

Table 13: Mineralogical composition results on the brick sample taken by CTP.

From the results, the main component is the quartz, demonstrating the difficulties faced (see Chapter 3) during the reduction of the granulometric distribution, for the d50, through the grinding by the ball mill.

Secondly, as for the limestone filler, the material is treated through the X-ray fluorescence to understand the chemical elements which compose its structure. The results are shown in Table 14.

[4] by Adèle Grellier, a Ph.D. student at the IMT Lille Douai, in 2018.

Element (oxide)	Brick (%)
SiO_2	**63.44**
Al_2O_3	**10.11**
Na_2O	0.13
K_2O	2.11
MgO	2.32
Fe_2O_3	**16.60**
Cr_2O_3	0.13
TiO_2	2.48
ZrO_2	0.13
P_2O_5	0.06
Mn_2O_3	0.22
Fire loss (1050 °C)	**0.525**

Table 14: Results of the X-ray fluorescence on the brick sample taken by CTP.

As we can understand from the results, the bricks are mainly composed of silica, alumina and ferric oxides. Indeed, the bricks, usually based on clay materials, may present some variation in the chemical composition, depending on their origin. However, in general, they are composed by kaolinite ($Al_2O_3.2SiO_2.2H_2O$).

5.5.1 Recycled brick's filler

Volumetric mass

The first step on the recycled filler is the analysis of the volumetric mass through the pycnometers.

Absolute density (kg/m^3)	Glass pycnometer	2861
	Helium pycnometer	3074

Table 15: The absolute and real density measured by the glass and the helium pycnometers.

The results in Table 15 show the higher values of the real density, in the case of the helium pycnometer measurement, for the brick's filler compared to the limestone filler. While for the tests performed using the glass pycnometers, the final value was lower with regard to the one showed by the limestone filler. As seen previously, the measure on the limestone filler was carried out with Helium pycnometer. The results in Table 15 are just the averages of the value measured during the tests. While the values recorded for each pycnometer are depicted in Annex 8.

Consequently, for the following computation regarding the mix design phase of the mortars, the value related to the helium pycnometer test is used for both the materials. The substitution of limestone filler by brick's filler will be carried out through a volumetric substitution, due to the differences in the densities, which means that the volumetric mass analysis is fundamental in both cases. The high volumetric mass presented by the brick's samples will influence the physical characteristics of the mortars, as will be shown in the related chapter.

Specific surface (Blaine test)

The specific surface was studied, as for the limestone filler and the cement, through the Blaine test, where the final value is computed through an indirect analysis. The test was performed on thee samples of material with the following mass (Table 16).

Mass (g)	Sample 1	2.66
	Sample 2	2.67
	Sample 3	2.68

Table 16: Sample masses used for the specific surface analysis through the Blaine test.

The repetition for three times is necessary to achieve the representative result (Table 17), with a low standard deviation.

Specific surface area (cm^2/g)	1835

Table 17: Specific surface measured through the Blaine test.

The brick filler presents a lower value compared to the limestone filler (3174.88 cm^2/g). This behavior can be explained by the physical characteristics of the recycled material after the crushing stages. The gradual reduction of the granulometry, during the preparation of the material, can lead to the rupture of the pores, progressively decreasing the specific surface area of the particles.

Granulometric analysis

From the distribution of the particles size measured through the particle size analyzer CILAS 1180L, the granulometric curve (Figure 44) shows a monodisperse trend with the majority of the diameters between 100 µm and 10 µm. This tendency is depending on the composition of the brick's material. Indeed, the bricks are made mainly by quartz sand, which is more difficult to be crushed due to its hardness.

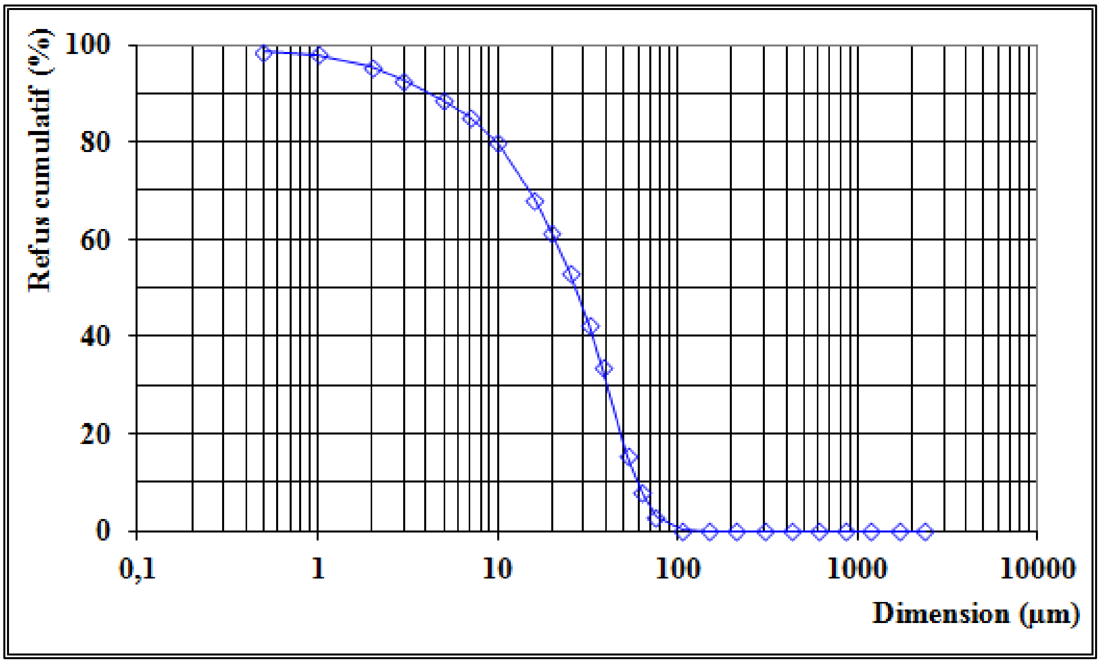


Figure 44: Particles size distribution performed by the CILAS 1180L analyzer (CTP, 2018).

The granulometry of the brick filler was studied through the laser diffraction in humid conditions (Figure 45). The particles size distribution was compared with the granulometric distribution of the limestone filler already obtained.

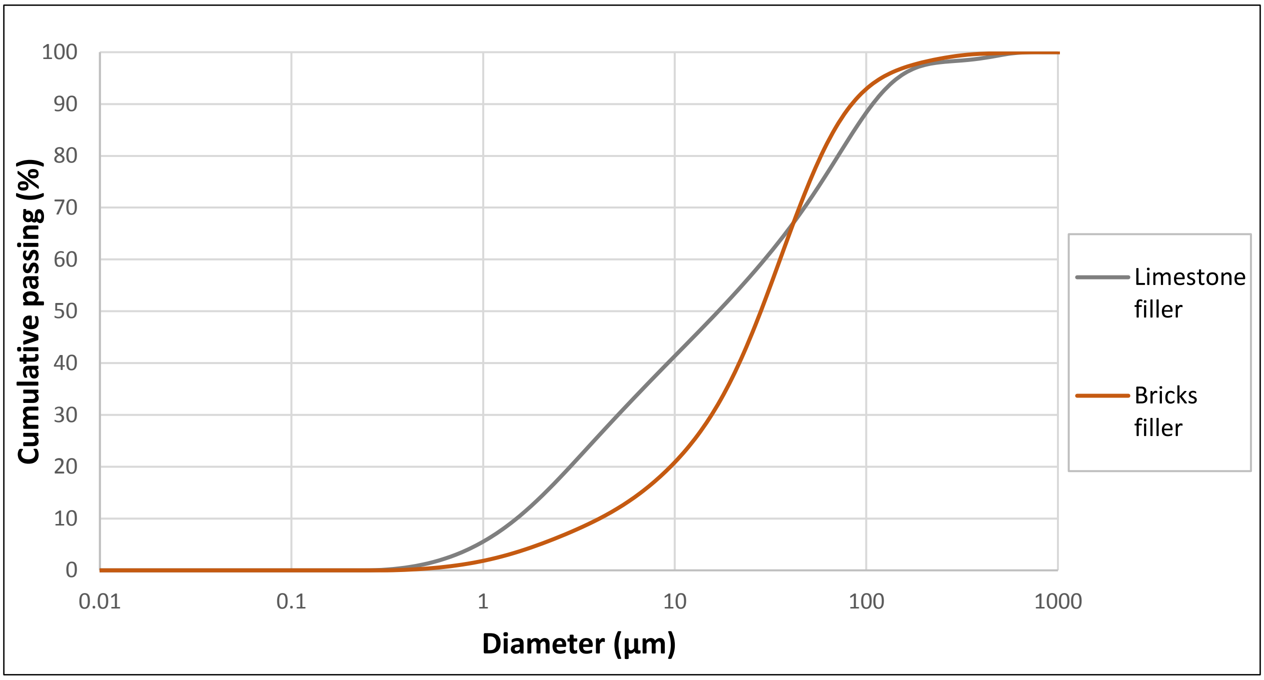


Figure 45: Comparison between the particle size distributions of the brick filler and limestone filler.

On one hand, the brick filler shows a coarser distribution together with a monodisperse behavior of the curve. On the other side, the limestone filler presents a larger portion of finer particles, with a more uniform distribution of the grains' diameter.

β_p analysis

The analysis was performed on the brick's filler, through the evaluation of six trials of pastes. In this way, the number of results was sufficient to study the relation between the water-powder ratio and the relative flow area. The results were the compared with the values obtained by another research5 on the limestone filler (Figure 46).

The limestone filler presents a lower βp compared to the brick filler, which can be justified by the finer and more uniform granulometric distribution. The voids, for the interstitial water, are covered by the particles of the limestone filler.

Due to the monodisperse distribution of the brick filler, the higher quantity of particles with the same dimensions causes the creation of the voids between them. Regarding the deformation coefficient, the brick filler material has a higher value demonstrating a more sensible behavior to the modifications on the water quantity used during the tests.

[5] By Mohamed Elkarim Bouarroudj, Ph.D student at the University of Liège, in 2017.

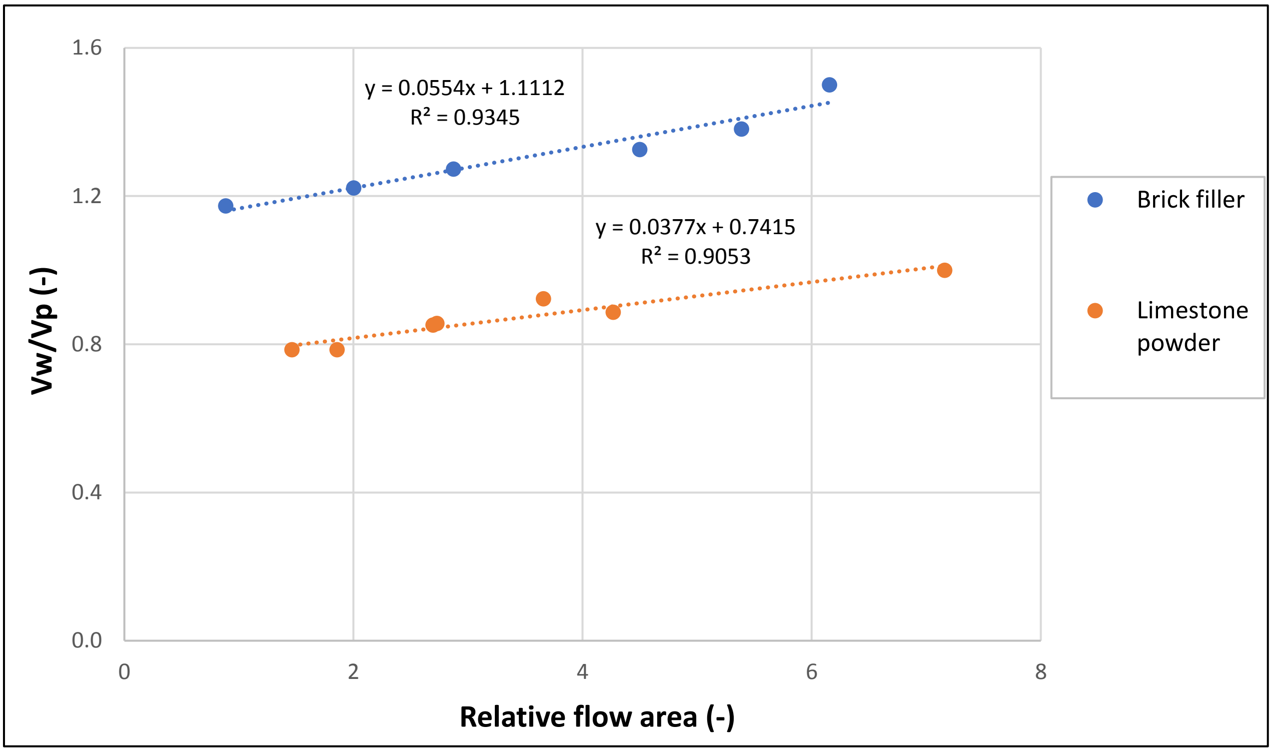


Figure 46, Limestone and brick filler linear relation between relative flow area and water powder ratio.

The data used for comparison between the brick filler and the limestone filler in this analysis are depicted in Annex 9.

Vicat test

Several mixes and trials were studied to achieve the 6 mm of the steel plunger sinking, as specified in the European Standard EN 196-2 [78]. Following the test procedure, the same amount of brick filler was used for the trials (500 g). The final value of water addition is depicted in following Table 18.

Water mass added to reach the rod sinking of 6 mm for the Vicat test (g)	180.87

Table 18: The water quantity to achieve the 6mm of the plunger sinking.

Knowing the water absorption (W_{A24h}) and the absolute density (ρ_{abs}), obtained by the helium pycnometer, the porosity can be computed through the following formula:

$$\varphi = \frac{W_{A24h}}{W_{A24h} + \frac{1}{\rho_{abs}}}$$

The data used for the computation, and the porosity calculated are depicted in Table 19.

$\boldsymbol{W_{A24h}}$ (%)	11.41
$\boldsymbol{\rho_{abs}}$ (g/cm³)	3.07
$\boldsymbol{\varphi}$ (%)	25.90

Table 19: The data for the computation and the porosity calculated.

Through the porosity value, the real density of the brick filler is computed with the following formula. The resulting real density value is depicted in Table 20.

$$\boldsymbol{\rho_{real}} = \boldsymbol{\rho_{abs}}\,(1-\boldsymbol{\varphi}\,) = \boldsymbol{\rho_{abs}}\,(1-\boldsymbol{\varphi}\,)$$

$\boldsymbol{\rho_{real}}$ (g/cm³)	2.28

Table 20: The real density of the brick filler.

In the end, thanks to the densities (ρ) and the ratio between the water and the filler in the paste (w/p), is possible to compute the real and the absolute compactness through the following formula:

$$\boldsymbol{\Phi} = \frac{\mathbf{1}}{\mathbf{1}+\boldsymbol{\rho}\frac{\boldsymbol{w}}{\boldsymbol{p}}}$$

The results coming from the computations are depicted in Table 21.

Compactness (%)	Absolute density	47
	Real density	55

Table 21: The absolute and real compactness computed for the brick filler paste.

The compactness value represents the quantity of material's particles inside a given volume of mix, in which is considered also the air present inside and between the grains. It's strictly linked to the particles' size distribution. If the material has a monodisperse distribution, as in the case of the brick filler, the particles cannot fill all the voids between them due to their similar dimensions. This leads to more spaces between the grains, increasing the hosted air and decreasing the final compactness of the mix.

GranuHeap

In this specific case study, the test was performed on three different samples to make the comparison between the brick filler, the limestone filler and the Portland CEM I 52.5 N. Thanks to the analysis, the repose angle (α_r) and the cohesiveness of the materials was computed. The test procedure, described in the Chapter 6, produced the following results (Table 22).

	α_r (°)	σ	Cohesion (-)	σ	Height (mm)	σ
Brick filler	64.2	0.6	1.7	0.4	37.2	0.1
Limestone filler	52.0	0.6	0.9	0.3	22.2	0.02
Cement CEM I 52.5N	68.7	1.1	7.0	2.0	36.6	0.1

Table 22: Results from the GranuHeap test.

The results show the higher cohesiveness for the cement fraction, with the higher angle of the heap during the test. However, the filler made of bricks presents also interesting results. The angle and the cohesion computed through the GranuHeap test are higher respect to the ones shown by the limestone filler. These outcomes are also justified by the high difference between the heights recorded for the two heaps of the materials.

The test was conducted each time on three samples of the same materials in order to chive the most representative values. The standard deviation obtained by the analysis of the three kinds of material is lower enough to consider this test reliable and repeatable in an efficient way.

GranuPaq

For the analysis on the packing density, the brick filler and the limestone filler are compared through the GranuPaq test. As for the GranuHeap test, the analysis is performed on three sample for each kind of material. The results are depicted in Table 23.

	ρ [0] (g/ml)	ρ [500] (g/ml)	n½	H_r	C (%)	ρ_∞ (g/ml)
Limestone filler	0.949	1.466	37.5	1.544	35.23	1.673
Brick filler	0.942	1.325	41.1	1.407	28.93	1.479

Table 23: The results coming from the GranuPaq analysis for the limestone filler and the brick filler.

The results show generally a lower packing density for the brick filler versus limestone filler. The final packing density *ρ[500]* of the brick filler presents a lower value, due to the monodisperse distribution of particles, which does not allow a good compactness. The higher compaction of the limestone filler, compared to the brick filler, is also shown by the higher Hausner ratio H_r and coefficient C, which define the relationship between the initial and final densities, through the following formulas:

$$Hr = \frac{\rho[500]}{\rho\ [0]}$$

$$C = \frac{\rho[500] - \rho\ [0]}{\rho[500]} * 100$$

GranuDrum

In this case study, the brick filler and the cement were tested with the GranuDrum analysis to compare the friction angles and the cohesiveness of the two materials. The test was performed both with the increase and the decreasing of the rotation speed. The results shown a similarity between the decreasing and the increase stages of velocities. For this reason, the trends obtained with the decreasing velocity stage are depicted in Annex 8. In the end, the flowing angle (Figure 47) and the dynamic cohesive index (Figure 48) were computed for each prefixed rotation speeds.

Considering the flowing angle (α_f), the brick filler shows a lower value compared to cement for each rotation speed, without taking into account the initial velocity of 2 rpm. So, the cement, according to its trend, is less flowable with regard to the brick filler. In the case of the less cohesive material, it is found that the flowing angle shows an increase with the higher rotation speeds.

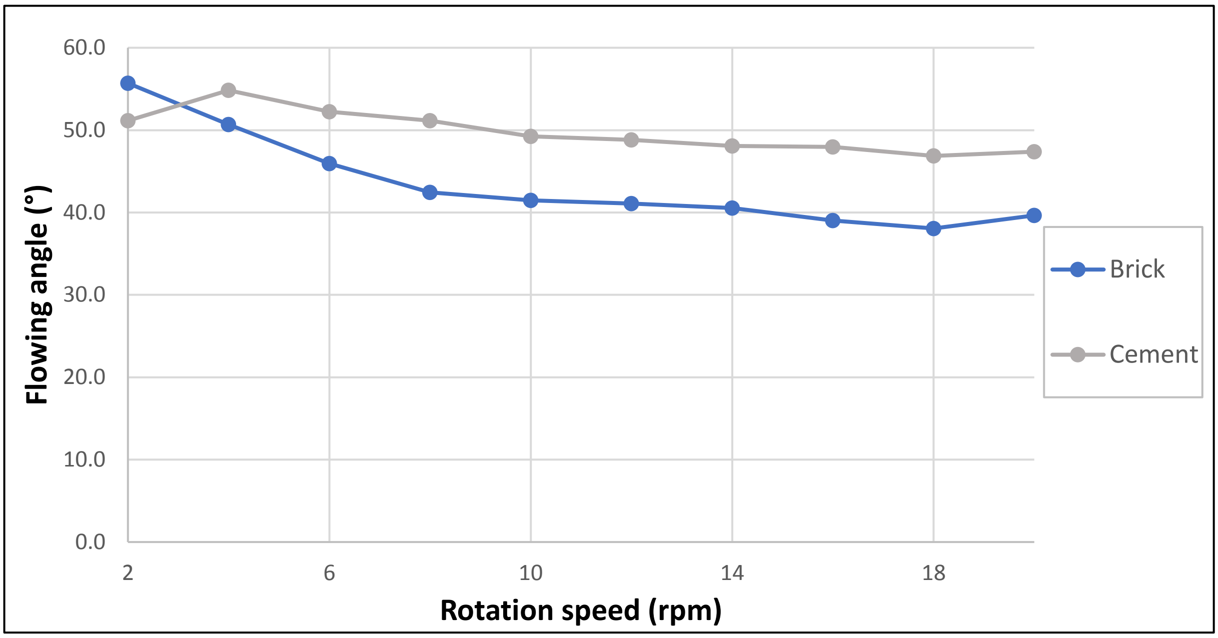


Figure 47: Flowing angle trend for the brick filler and the cement CEM I 52.5N during the GranuDrum test.

Considering the cohesion computed during the test (Figure 48), the same aspects displayed by the flowing angle are present. Indeed, even if the trends of the brick and the cement are similar, in general, the second material presents a higher cohesion.

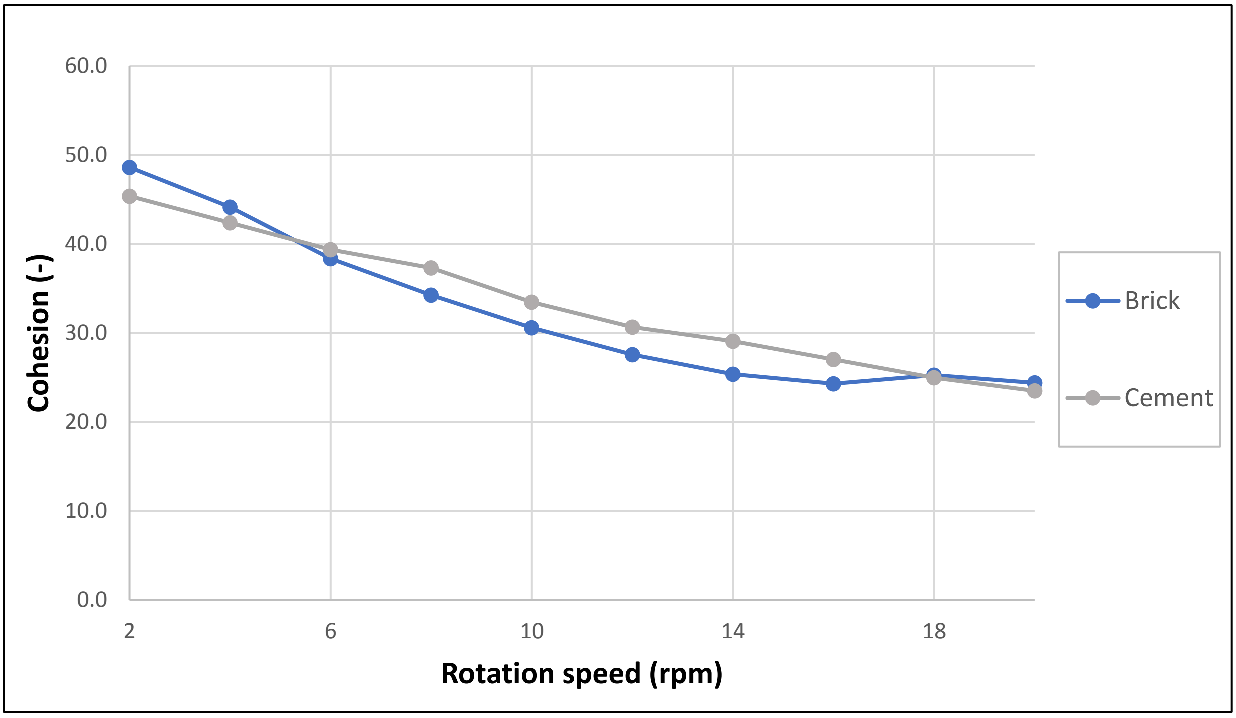


Figure 48, Cohesion's trend for brick filler and cement CEM I 52.5N during the GranuDrum test.

5.5.2 *Recycled brick's sand*

Volumetric mass

The test was performed for three times with the stainless-steel pycnometer to achieve a representative result. The average value of the three samples analyzed is depicted in Table 24.

Absolute density [kg/m³]	2673

Table 24: Absolute density of the brick sand obtained through the stainless-steel pycnometers.

The result is slightly lower than the value obtained for the brick's filler with the helium pycnometer. However, the granulometry of the material is larger, leading to more voids between the particles.

Moreover, the larger grains, respect to the filler, can be still characterized by an important porosity. This can decrease the weight of the sample leading to the reduction of the final density.

The value depicted in Table 24 is the average of the results obtained for the brick sand. However, in Annex 10 are presented all the values measured with the pycnometers.

Granulometry

The brick's sand was first dried in the oven at 105°C for at least 24 hours to reduce as much as possible the humidity still presents in the particles. Thanks to the drying stage, the results were obtained without any problem regarding the agglomeration of particles.

To have the most representative results, the sieving was performed on three samples of 300 g through the vibratory sieve in three different stages (Figure 49). The detailed masses and the percentages of the size fractions are presented in Annex 6.

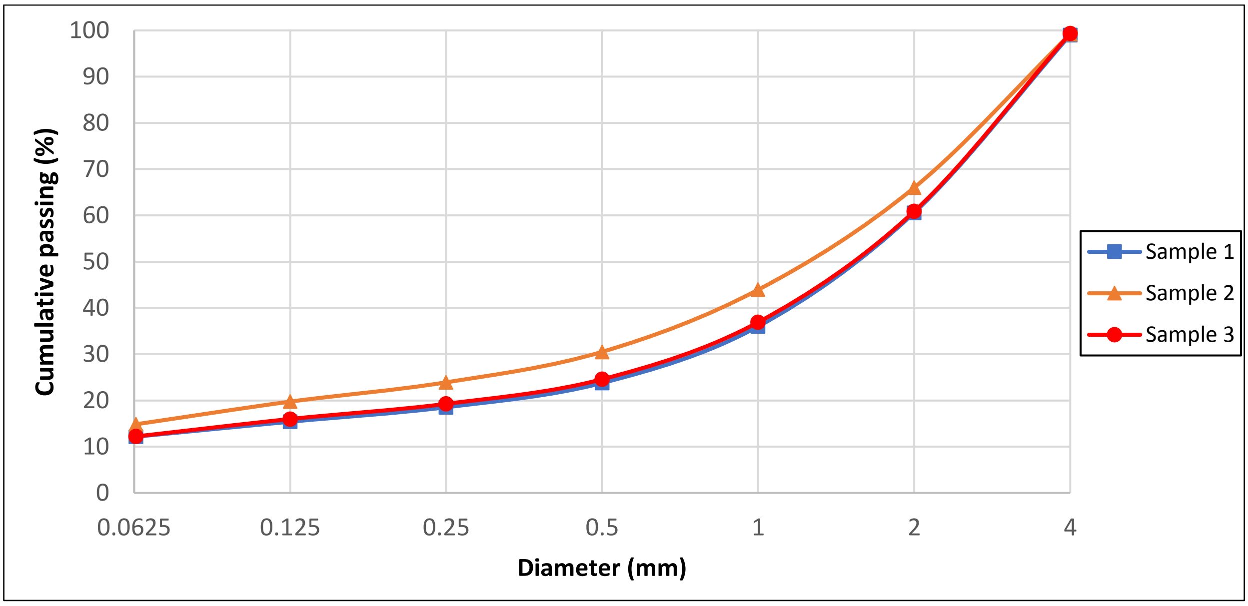


Figure 49, Particles size distribution of the brick's sand [0; 4 mm].

The distribution of the granulometries show most of the particles with a diameter below 2 mm, and a passing percentage over 60%. However, below this limit, the particles are well distributed in the finer diameters.

Comparing the granulometric distribution between the brick sand and the limestone sand (Figure 42), the first presents a larger percentage of coarser particles.

Water absorption analysis

The analysis of the water absorption is conducted on two different granulometric fractions of the bricks (Figure 50): the crushed bricks, with a granulometry of 0/30 mm, and the brick sand, with a range of diameters equal to 0/4 mm. Both the IFSTTAR and the European standard method were performed, with different results.


Figure 50: 0/10 mm bricks' fraction, on the left, and brick's sand 0/4 mm, on the right

The test is performed on four samples for each type of material following the same procedures. However, only the results coming from the IFSTTAR test are taken for the next analysis of the mortar. In fact, the water absorption coefficients obtained with the standard method showed uncoherent values, according to the literature.

The average data recorded during the IFSTTAR method for the brick sand are displayed in Table 25.

M_w (g)	304,15
M_d (g)	264,5
W_{A24h}(%)	15,1
σ (-)	0,48

Table 25: The water absorption results obtained through the IFSTTAR method on the brick sand [0; 4 mm].

The same analysis was done on the fraction 0/30 mm. In this case, during the test procedure, the phenomena of agglomeration were absent due to the lower presence of fine particles. Furthermore, the drying phase through the paper, resulted to be easier compared to previous material. From the test, the following mean values were obtained (Table 26).

M_w (g)	918.63
M_d (g)	824,73
W_{A24h}(%)	11,41
σ (-)	0,26

Table 26: The water absorption results obtained through the IFSTTAR method on the crushed bricks [0; 30 mm].

To produce and design the mortar samples, the water absorption of the crushed bricks is taken into account. Indeed, the bricks' porosity is not dramatically changed during the crushing procedure through the jaw crusher and the ball mill and it permits this condition. The results coming from the water absorption test are depicted in Annex 11.

6. Recycling bricks for SCM

Two compositions were produced. The first was used for the analysis on the fresh and the rheological properties. While the second, was then adopted for the production of the mortar samples analyzed on the hard properties.

Both the two compositions were derived by the study on a self-compacting concrete produced in the University of Liège[6] (Table 27). The concrete equivalent mortar method (CEM) presented in the Chapter 4 is used to transform the concrete mix in the mortar for the analysis.

Constituent	M_v [g/cm^3]	Mass for 1 m^3 of SCC [kg]
CEM 1 52,5 N	3.1	311
Limestone filler	2.71	207
Normalized sand	2.65	918
Aggregates 2/7	2.71	295
Aggregates 7/14	2.71	554
Efficient water	1	165
Admixtures	1.1	6,531 *(2,1% of the cement quantity)*

Table 27: The composition of the self-compacting concrete taken as reference.

Each material quantity is transformed to allow the production of the mortar, through the following formula.

$$V\ (mortar) = \frac{mass\ for\ 1\ m^3 of\ SCC}{M_v}$$

$$Total = \sum V\ (mortar)$$

Then, the resulting volume is converted for the production of 1 m^3 of mortar:

$$V\ (1m^3) = \frac{V(mortar) * 1000}{Total}$$

Finally, the mass of each material for 1 m^3 of mortar is computed with the following formula:

$$M\ (1m^3) = V(1m^3) * M_v$$

Moreover, in this case, study, as already mentioned before, the superplasticizer is not used for mortar mixes in order to enhance the behavior of the brick filler. For this reason, the fractioning of the constituents is, for some material, further different.

[6] By the PhD student Mohamed Elkarim Bouarroudj for his research in 2017.

After the knowledge of the composition for the production of 1 m^3, a proportion is used to make the right quantity of self-compacting mortar for the molds of this work study.

6.1 Experimental program on the SCM

The several samples of mortar were produced in the Laboratory of Building Materials in the University of Liège[7]. The investigation started with the choice of the self-compacting mortar composition. In this case, the same composition of the Self-compacting concrete, produced by the PhD student Mohamed Elkarim Bouarroudj for his research, was used. However, the coarse aggregates fraction was not added inside the mix, in order to obtain a mortar product. The investigation was divided into two sections. The first concerning the replacement of the limestone filler by the bricks filler. The second, about the substitution of the limestone sand by the bricks sand (0/4 mm). In both the situation, after the mixing procedure, the fresh properties were first recorded and interpreted. Then, after the period of hardening, the properties of the samples were investigated.

All the self-compacting mortar samples were produced following the same protocol of mixing. The procedure can be summarized in the next points:

1. Humidify the container of the mixer;
2. Insert the materials into the container;
3. Start the mixer for 30 seconds at the lower velocity;
4. Add the quantity of water required for the mix;
5. Start the mixer for 90 seconds at the lower velocity;
6. Stop the mixer and wait for 60 seconds;
7. Restart the mixer for 30 seconds at a low velocity
8. Increase the velocity for 60 seconds;

However, for the case of the limestone sand substitution, the procedure differs in some steps:

1. Humidify the container of the mixer;
2. Insert the pre-saturated material into the container;
3. Start the mixer for 120 seconds at the lower velocity;
4. Stop the mixer and wait for 60 seconds;
5. Restart the mixer for 30 seconds at a low velocity
6. Increase the velocity for 60 seconds;

For the investigation of the fresh behavior and properties of the samples, the following tests were performed:

- The slump-flow test, according to the EFNARC standards [55], to study the deformability of the mixtures through the mini cone and the MBE cone (Figure 51). The test consists, first, in the introduction of the mixture inside the steel cone molds without the compaction of the material. Then, the mold is removed as vertically as possible and the measure of the mix spread performed. From the measure of four diameters, the consistency of the mortar is analyzed together with its fluidity and workability.

[7] With the collaboration of Mohamed Elkarim Bouarroudj, Ph.D student at the University of Liège, in 2018.

Figure 51: Mini cone (right) and MBE cone (left) for the slump tests.

- *The air content test,* according to the norm EN 413-2 [85]: the aerometer is filled by the mortar, closed and brought under pressure (Figure 52). This method is based on the compressibility of the air still present inside the fresh mortar. Thanks to the pressure recorded during the test, the air content of the samples is obtained.

Figure 52: Aerometer of 750 ml for mortar analysis [86].

- *Volumetric mass analysis* through the stainless-steel pycnometer with known mass and dimensions. The pycnometers are weighed empty, filled with water and by the material to compute the final volumetric mass of the mortar.
- The rheologic properties of the mortars samples were analyzed by the *RheoCAD*. The device imposes several rotation velocities, for a constant time interval, on the material introduced in the container (Figure 53). During these intervals, the *RheoCAD* records the resistant torque resulting [87].

Figure 53: the RheoCAD apparatus [87].

The analysis of the replacement influence by the bricks on the resistance torque is measured through a rotation program, with fixed rotation speed, which allows the correlation between the results obtained and the spread found by the slump tests. The program followed by the *RheoCAD* is displayed in Figure 56.

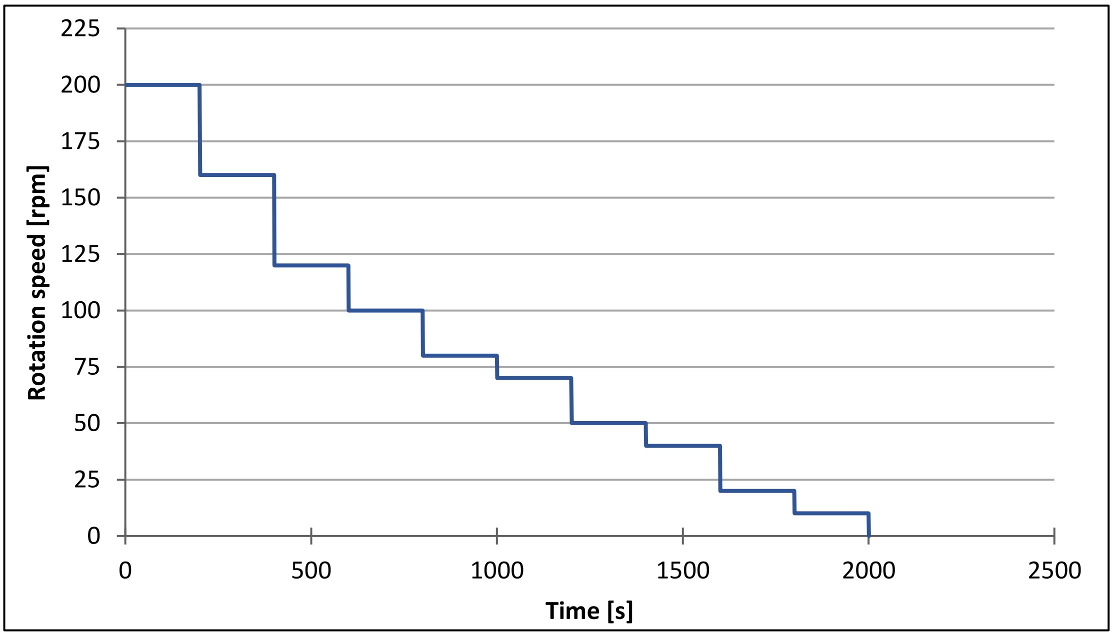


Figure 54: The RheoCAD program chosen for the tests

The speed of rotation decreases gradually, preventing the phenomenon of thixotropy. The thixotropy consists of the viscosity reduction during the application of the shear stress applied to the material. This situation is reversible because the material can regain its initial viscosity when the stress is not more applied. The phenomenon is caused by the temporary destruction of the material cohesion under the effect of a sufficiently high shear stress. This generates an apparent reduction of the viscosity. At the removal of the shear stress, the material recuperates its original cohesion, leading to an apparent increase in the viscosity.

Regarding the mortar samples at the hard state the following tests were performed:

- *Compressive strength test* at 7 days and 28 days for the filler replacement. While for the sand replacement the test is performed at 14 days and 28 days. The test was performed on samples obtained after the flexural strength analysis, according to the European norm EN 196-1;
- *Flexural strength test* at 7 and 28 days for the filler replacement. While for the sand replacement at 14 and 28 days. The mortar samples were produced in the form of a prism with 4x4x16 cm^3 of dimensions, according the European norm EN 196-1;

6.2 Bricks for limestone filler substitution

The first phase of the analysis concentrated the attention to the substitution of the limestone filler by the brick filler, already characterized and presented in the previous chapters. The impact of the partial replacement is studied through the analysis of the fresh and hard properties of the mortar mixes produced. The substitution, due to the differences in the density between the two type of material, was performed in a volumetric way.

Reference mortar (BF-0)

For the first analysis, the reference mortar (BF-0: Brick Filler-0) was produced using the usual materials for the self-compacting mortar. The final composition, computed through the previous method, created two compositions. The first, in Table 28, was used for the study on the fresh properties of the mortar, as the slump test, the air content measurement and the analysis of the rheological properties.

Sample	Replacement (%)	Cement (g)	Limestone powder (g)	Brick powder (g)	Efficient Water (g)	Water abs. (g)	Normalized sand (g)
BF-0	0	448	298.33	0	358.4	0	1350

Table 28: Reference mortar composition for the firsts analysis

The second composition was obtained through the increases by three times of the previous one, to produce the samples of the mortars and study the hard properties (Table 29). The increase of the constituents allows the production of sufficient mortar to produce enough samples for the mechanical properties study.

Sample	Replacement (%)	Cement (g)	Limestone powder (g)	Brick powder (g)	Efficient Water (g)	Water abs. (g)	Normalized sand (g)
BF-0	0	1344	894.99	0	1075.2	0	4050

Table 29: Reference mortar composition for the analysis on the hard properties.

Mortar with recycled bricks

In this case, the gradual replacement is performed through a volumetric substitution of the limestone filler through the following formula. For each of the mixes, the quantity of brick filler needed is computed.

$$M_{Brick\ filler} = \frac{M_{Limestone\ filler}}{M_{v,limestone\ filler}} * M_{v,brick\ filler}$$

Moreover, in this study, the tests were reproduced considering also the water absorption of the bricks (see Chapter 4). Although the filler, due to their low particles size distribution, are not usually testes considering the water absorption, in this situation the analysis was performed to verify the presence or not of the microporosity. Two kinds of samples were produced. The first, BFNWA (Brick Filler No Water Absorption), neglects the water absorption of the brick fraction. The second, BFWA (Brick Filler Water Absorption), considers the possible absorption of the brick particles. Indeed, form the tables, the mixing water used inside the production of some mortars takes into account both the efficient water and the possible water absorbed by the brick filler. In the end, the limestone filler was partially replaced by the brick filler for 50% and 100% on the volume.

As for the reference mortar, two compositions were made. The first was produced for the analysis of the fresh and the rheological properties (Table 30). While the second, was studied to investigate the hard properties (Table 31).

Sample	Replacement (%)	Cement (g)	Limestone Powder (g)	Brick Powder (g)	Efficient Water (g)	Water absorbed (g)	Normalized sand (g)
BFWA-50	50	448	149.17	168.09	358.4	18.49	1350
BFWA-100	100		0	336.19		36.98	
BFNWA-50	50		149.17	168.09		0	
BFNWA-100	100		0	336.19		0	

Table 30: Mortar composition for the firsts tests on the fresh properties.

Sample	Replacement (%)	Cement (g)	Limestone Powder (g)	Brick Powder (g)	Efficient Water (g)	Water absorbed (g)	Normalized sand (g)
BFWA-50	50	1344	447.51	504.27	1075.2	55.47	4050
BFWA-100	100		0	1008.57		110.94	
BFNWA-50	50		447.51	504.27		0	
BFNWA-100	100		0	1008.57		0	

Table 31: Mortar composition for the analysis of the hard properties.

6.3 Bricks in the limestone sand substitution

In this second phase of the investigation, the impact in the mortar by the brick sand, already characterized in Chapter 4, is analyzed. As in the previous case, the influence of the recycled fraction is studied through the fresh and the hard properties of the mortar produced. For this reason, were created two kind of compositions to tests the fresh and hard behaviors.

Respect to the filler substitution case, in which the normalized sand was used, the sand fraction in this situation was the limestone sand, produced by Carmeuse in Engis, already characterized. Although the granulometric distribution of the two materials is similar, the water absorption differs a lot. However, the lower water absorption by the limestone sand allows the enhancement of the brick sand behavior and a better study of its influence on the mortar.

The same composition of the Self-compacting concrete presented for the filler substitution case was used for this partial replacement study. As in the previous situation, the gradual replacement by the brick sand is performed through a volumetric substitution due to the differences in the volumetric masses of the two materials.

Reference mortar (BS-0)

For the firsts analysis, the reference mortar (BS-0: Brick Sand-0) was produced. Even if the limestone sand presented a low water absorption during the characterization step, the material was pre-saturated 24 hours in the mixing water before the preparation of the mortars. Moreover, the mixing water counts both for the efficient one and for water which can be possibly absorbed by the sand fraction. The first composition is displayed in Table 32.

Sample	Replacement (%)	Cement (g)	Limestone filler (g)	Eff. Water (g)	Limestone sand (g)	Brick sand (g)	Water abs.(g)	Total water (g)
BS-0	0	448	298.33	403.2	1350	0	2.98	406.18

Table 32: Reference mortar (BS-0) composition for the analysis on the fresh properties

For the analysis of the hard properties, after the periods fixed, the composition displayed in Table 33 is chosen.

Sample	Replacement (%)	Cement (g)	Limestone filler (g)	Eff. Water (g)	Limestone sand (g)	Brick sand (g)	Water abs.(g)	Total water (g)
BS-0	0	1344	895.00	1209.6	4050	0	8.95	1218.55

Table 33: Reference mortar composition for the hard properties analysis.

Mortar with recycled bricks

As for the filler substitution case, the mortar produced with the addition of the brick sand is characterized by the gradually volumetric replacement of the limestone sand.

The water absorption in this situation covers a considerable role for the composition and the behavior of the final samples. The value considered during the mortar mix design is derived from the water absorption test performed through the IFSTTAR method during the characterization of the material (Chapter 5.5.2). The result obtained on the coarser pieces of bricks is used for the analysis, respect to the one produced by the sand fraction (Table 34). This choice is related to the more representative porosity of the bigger pieces of bricks.

W_{A24h}	Water absorption coefficient of the brick (%)	11.41

Table 34: Bricks water absorption.

Sample	Replacement (%)	Cement (g)	Limestone filler (g)	Eff. water (g)	Limestone sand (g)	Brick sand (g)	Water abs. (g)	Total water (g)
BS-5	5	448	298.33	403.2	1282.5	56.02	9.15	412.35
BS-10	10				1215	112.04	15.31	418.51
BS-25	25				1012.5	280.09	33.79	436.99
BS-50	50				675	560.18	64.60	467.80

Table 35: Mortar composition for the fresh properties study.

Due to the absorption of the brick, the sand samples were pre-saturated for 24 hours in the mixing water before the production of the mortar, both for the study on the fresh and the hard properties. The mixing water, as in the reference mortar case, is made by the efficient water and by the water possibly absorbed by the brick sand. The partial replacement of the limestone sand, to study the fresh and the rheological properties, was performed in the following percentage: 5% (BS-5), 10% (BS-10), 25% (BS-25), 50% (BS-50) (Table 35).

However, due to the similar fresh behavior recorded for the reference mix and the samples BS-5 and BS-10, as will be showed in the following sections, the study of the mechanical properties is for the reference mix, the BS-25 and the BS-50 specimens (Table 36).

Sample	Replacement (%)	Cement (g)	Limestone filler (g)	Eff. water (g)	Limestone sand (g)	Brick sand (g)	Water abs. (g)	Total water (g)
BS-25	25	1344	895.00	1209.6	3037.5	840.27	101.38	1310.98
BS-50	50				2025	1680.55	193.81	1403.41

Table 36: Mortar composition for the hard properties study.

7. The results of fresh and mechanical properties

7.1 SCM with brick filler

In the following section, the results coming from the analysis on the self-compacting mortar produced with the partial limestone filler replacement by the brick filler will be presented. First the fresh properties and then the hard ones will be analyzed and compared to enlighten the influence of the recycled materials on the self-compacting mortar behavior.

7.1.1 Fresh properties

Slump tests

The first analysis performed on the mixes is the slump tests, respectively with the mini cone (Figure 55) and the MBE cone (Figure 56). The measurement of the spread and the thickness of the mortars are measured immediately after the removing of the truncated cones. The Figure 55 shows the comparison between the two kinds of mortar compositions after the test through the mini cone.

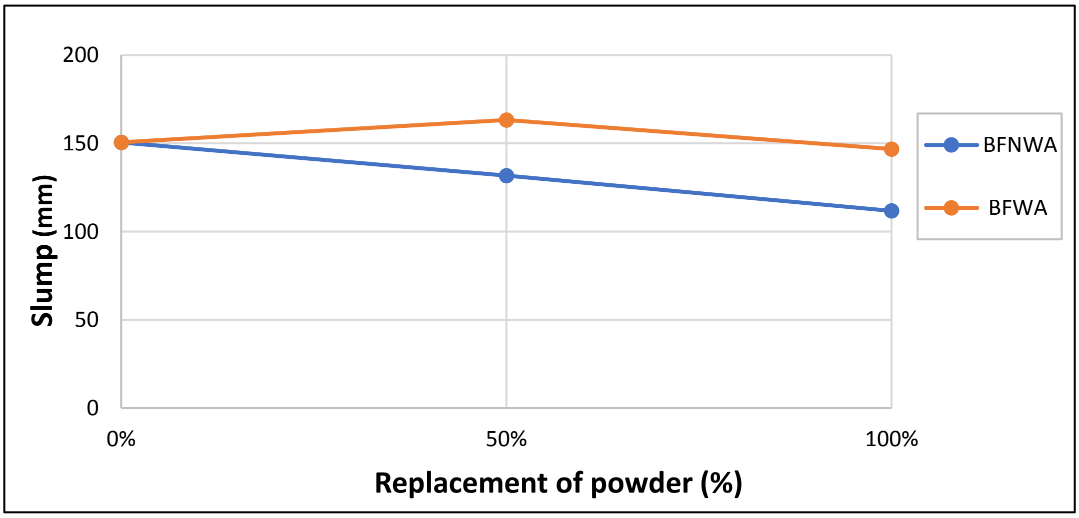


Figure 55: The slump test results from the mini cone test.

The trend of the mixes indicates different aspects. Considering the mix where the fraction of water is enough to face the possible water absorption of the brick filler, there are no significant changes from the reference mix. This could be related to the availability of enough water between the particles to allow the achievement of a higher workability and a better flowability.

Regarding the mortars with only the efficient water inside, the trend presents a slight decrease in the slump spread probably due to the role of the brick particles. Indeed, with the increase of the substitution rate of the limestone filler by the brick filler, the spread and the flowability start to decrease. Moreover, the water available inside the composition is not enough to ensure a good workability of the mortar.

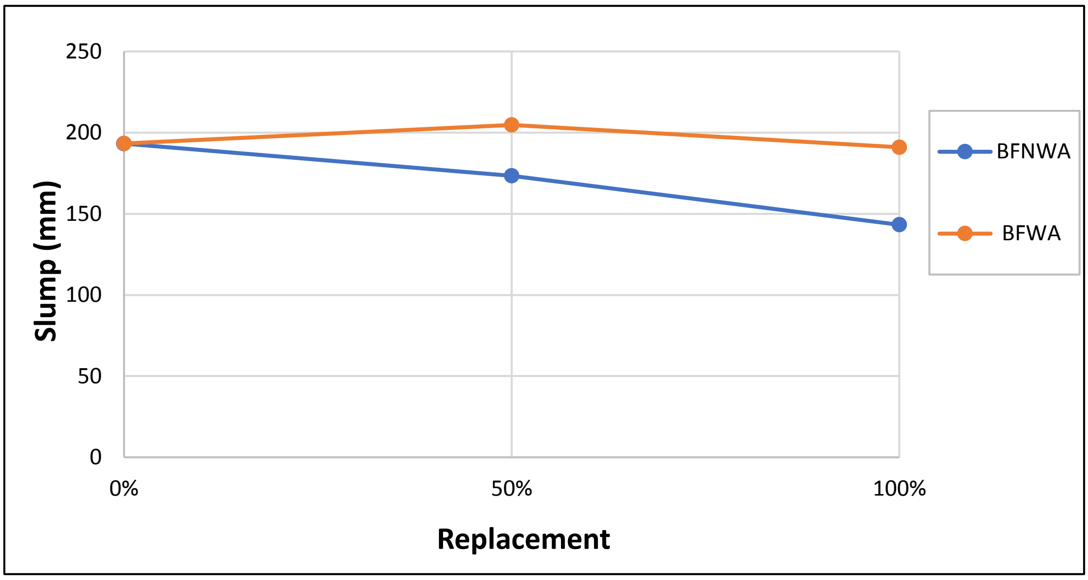


Figure 56: The slump test results from the MBE cone test.

The same test is performed through the MBE cone. The results present a similar trend of the spread mixes seen for the mini cone test (Figure 56). In the case of the BFWA samples, the increase of the replacement by the brick filler does not influence in a considerable way the final value of the slump test. Concerning the BFNWA samples, the increase of the brick filler leads gradually to the reduction of the final spread value.

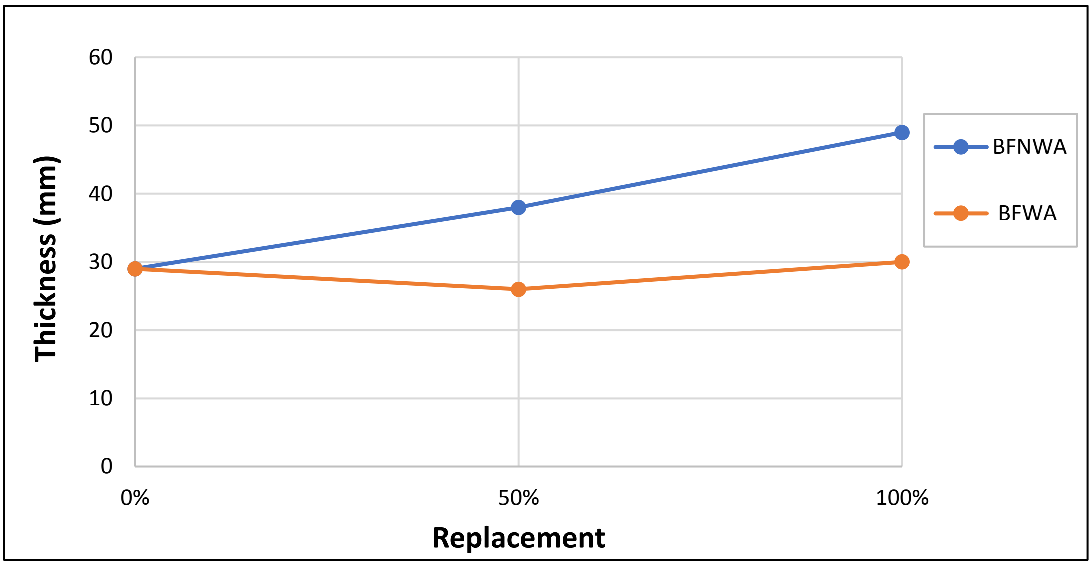


Figure 57: Variation of the thickness after the slump test by the mini cone.

After each slump test by the mini cone, the thickness of the spread is measured immediately after the diameters measurement (Figure 57). The value of the thickness is indirectly linked to the spread of the mixes. Indeed, the more the spread is higher, the less the thickness will be. This explains the higher settlements for the mixes with less quantity of water inside.

On the other hand, this justifies the lower thickness of the spreads with the higher quantity of water. Although for the BFWA samples the thickness of the BFWA-100 sample is higher respect to the BFWA-50.

All the results recorded during the slump tests through the two kinds of truncated cone are depicted in Annex 12.

Air content test

Through the aerometer and the measure of the air compressibility still present in the mix, the air content is obtained (Figure 58).

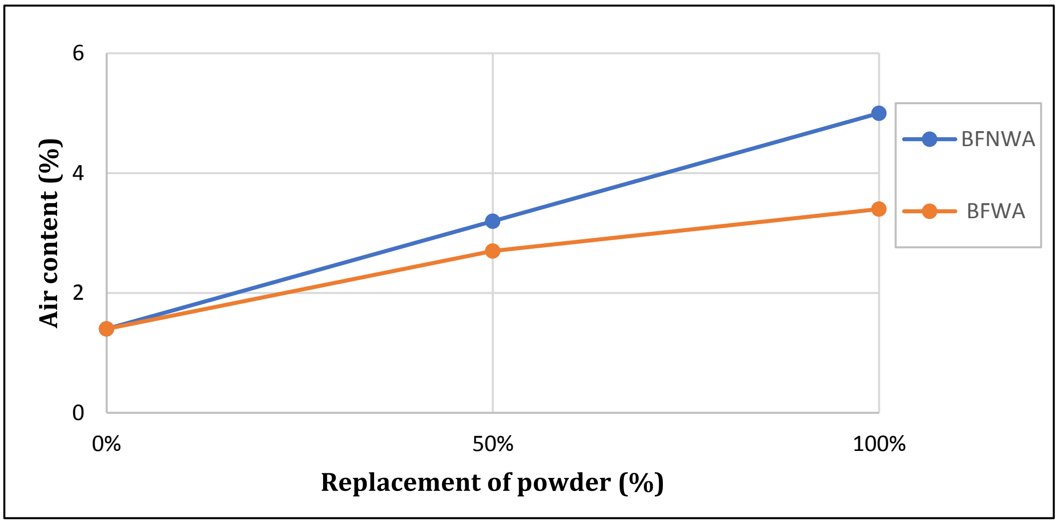


Figure 58: Air content variation in the mixes produced.

For all the mixes exanimated, the graph displays the increase of the air content in the composition. This trend can be related to different aspects. The particles size distributions of the brick filler, presenting a mono-disperse trend, increases the possibility to have more spaces between the grains which host the air.

Volumetric mass analysis

After the air content analysis, the volumetric masses of the mortars are computed through the stainless-steel pycnometers.

First, the pycnometers are weighed both empty and filled by water. Then, they are filled with the mortar samples to be again weighed.

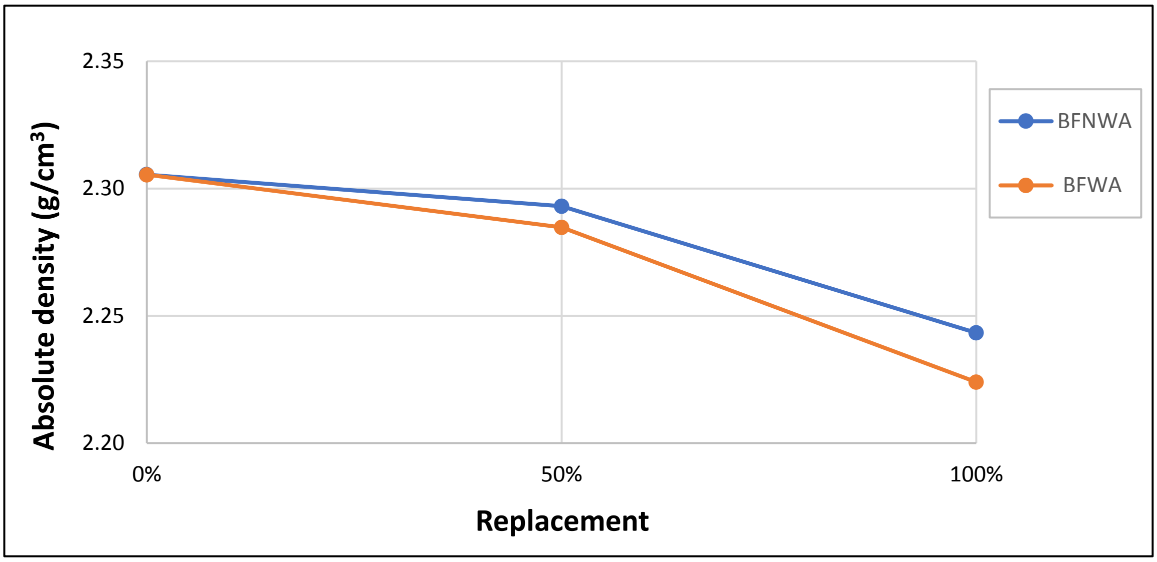


Figure 59: Absolute density variation for the mortar mixes.

From the Figure 59, regarding the samples BFWA-50 and BFWA-100, the absolute densities are lower respect to the reference mix. This result is directly correlated to the air content already seen previously. Indeed, with an increase of the air inside the mix, which has a lower density compared to the material, a decrease of the absolute density is recorded. The quantity of air increases with the increase of the brick filler, leading to a further decrease of the absolute density. The mixes BFNWA-50 and BFNWA-100 display the same behavior.

RheoCAD analysis

As already presented, the rheologic properties of the mixes are measured through the *Rheocad* apparatus. It, through the rotation speed fixed by the program, measures the resistant torque in Ncm, which is then converted to Pa. The program computes the average values of the resistant torque during the time interval where the rotation speed is constant. Each test on the mixes is performed guaranteeing the same intermission from the mixing procedure of the mortar and the *RheoCAD* test. To ensure the representative results, the apparatus is cleaned after each test and humidified to start the following one.

In Figure 60, the variation of the resistant torque as a function of the rotation speed is displayed. For all the mixes, an increase of the torque is recorded with the rise of the rotation speed. Generally, the rheological properties of the mortars are strictly linked to the flowability and workability aspects seen in the slump tests.

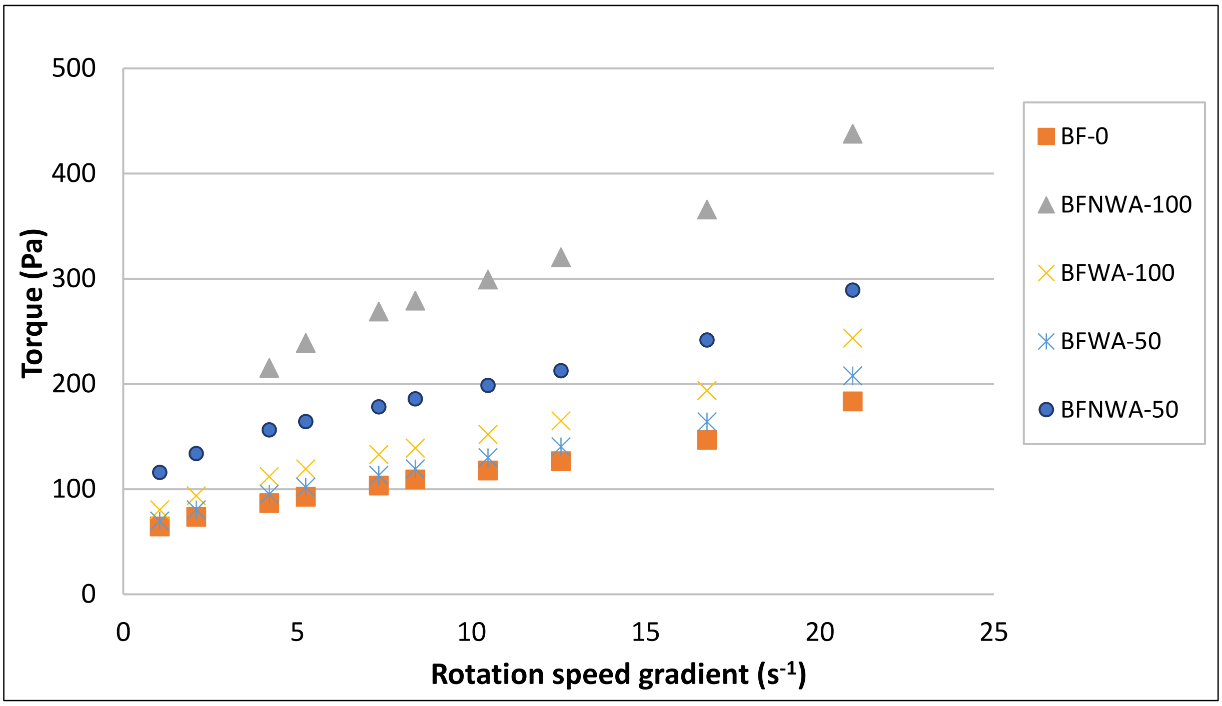


Figure 60: The torque variation in respect to the rotation speed for the mortar mixes.

Comparing the mixes, the relation with the slump tests is clear. The mortar BFNWA-100, which showed the lower value of spread, presents the higher values of torque for the rotation speed increase. The BFNWA-50 sample follows the same behavior, where the lower presence of water inside the composition led both to the lower spread and to the higher torque.

Concerning the mixes BFWA-100 and BFWA-50, the torque trend in the graph displays a similar behavior of the reference mix. This is remarked by the results obtained from the slump test, where the spreads were almost the same as the mix without the addition of the brick filler.

For each mortar is produced the trendline to understand the relationship between the resistant torque and the rotation speed (Annex 13). The equation of the trendline is then considered for the analysis of the materials as a Bingham plastic. The Bingham model can be summarized in the following equation:

$$\tau = \tau_0 + \mu\dot{\gamma}$$

Thanks to the trendlines computed, the starting shear stress τ_0 and the dynamic viscosity μ are obtained and displayed in Table 37.

Mortar mix	Equation	R^2	τ_0	μ
BF-0	$\tau = 61.52+5.51\gamma^{\cdot}$	0.99	61.52	5.51
BFWA-50	$\tau = 65.60+6.36\gamma^{\cdot}$	0.99	65.60	6.36
BFWA-100	$\tau = 76.03+7.55\gamma^{\cdot}$	0.99	76.03	7.55
BFNWA-50	$\tau = 117.04+7.95\gamma^{\cdot}$	0.99	117.04	7.95
BFNWA-100	$\tau = 171.16+12.32\gamma^{\cdot}$	0.99	171.16	12.32

Table 37: Mortar mixes value for the rheological properties.

From the values about the rheological properties, the mortar samples, which present the higher initial torque and dynamic viscosity, are the ones without the consideration of the water absorption by the brick filler. Indeed, a higher viscosity is linked to a higher torque during the *RheoCAD* test. On the other hand, the samples BFWA-50 and BFWA-100 have a lower viscosity and, as a consequence, a lower torque resistant. The trendline equation of the reference mortar indicates the low resistant torque together with the low viscosity.

These behaviors depend on the internal friction between the particles and the fluidity grade of the mortars. With the water addition, to face the possible absorption of the brick, the fluidity of the mix increases, leading to the decrease of the viscosity and the torque. While, if the water inside the mortar is less, the friction between the grains grows. This is depicted clearly by the BFNWA samples. However, in both the types of samples, the brick filler increases the internal friction between the particles, causing the increase of the torque and the viscosity. The reference mix, in the end, presented the lower torque and viscosity due to the higher flowability, which could be caused both by the different granulometric distribution and the higher availability of the water inside the mortar.

7.1.2 Hard properties

In this section, the results coming from the flexural and compressive strength tests will be presented. The tests were performed after 7 and 28 days. In Annex 16 the detailed results obtained by the different samples are shown, while, in this section, the average values of the parameters are depicted. In Table 38, the values for the flexural strength at 7 and 28 days of the samples are presented.

Sample	Flexural strength at 7 days (MPa)	Flexural strength at 28 days (MPa)
BF-0	6.71	7.38
BFWA-50	6.32	7.38
BFWA-100	5.25	7.11
BFNWA-50	5.85	6.98
BFNWA-100	5.69	7.72

Table 38: Flexural strength at 7 and 28 days for the filler substitution case.

From the difference of values, the brick filler addition leads to the slightly decrease of the flexural strength in the first period. However, after 28 days from the mortar production, there are not remarkable decreases of the flexural strengths.

Concerning the compressive strength (Table 39) after 7 days of interval, a slight decrease of values is recorded with the increase of the limestone filler substitution. On the other hand, after 28 days, the values have a general decrease for the samples BFWA-50 and BFWA-100, while for the mortars BFNWA-50 and BFNWA-100 there are some similarities compared to the reference mix.

Sample	Compressive strength at 7 days (MPa)	Compressive strength at 28 days (MPa)
BF-0	32.18	37.61
BFWA-50	31.31	36.37
BFWA-100	26.80	35.61
BFNWA-50	30.38	37.76
BFNWA-100	29.17	39.41

Table 39: Compressive strength results for the filler substitution case.

In this way, the variations in the composition and in the quantity of the mixing water, can influence the final mechanical properties of the mortar. Indeed, comparing the samples with 50% and 100% of replacement, the addition of water to face the possible absorption by the brick material leads to a decrease after 28 days. However, this is not confirmed by the 7 days case, where the sample BFWA-50 presents a similar compressive strength to the mortar BFNWA-50, as exposed in Table 39.

7.2 SCM with brick sand

After the analysis on the limestone filler substitution by the brick filler, the investigation continues with the study of the limestone sand replacement by the brick sand (BS). As for the previous analysis, the samples were analyzed on the fresh and hard properties, to compare and underline the differences between the mortars. However, in the sand case, the analysis is performed only with the pre-saturation of the material, performed for 24 hours before the mortars production.

7.2.1 Fresh properties

For the analysis of the fresh properties, the replacement of the limestone sand was performed for 0%, 5%, 10%, 25%, 50% on the volume. The same tests performed for the partial limestone filler replacement were used also for this study.

Slump test

After the mixing procedure, the slump test is performed through the mini cone and the MBE cone. The slump spreads are recorded for each test and the average of the diameters is displayed in the following graphs to understand the role of the brick sand in the workability of the mortar.

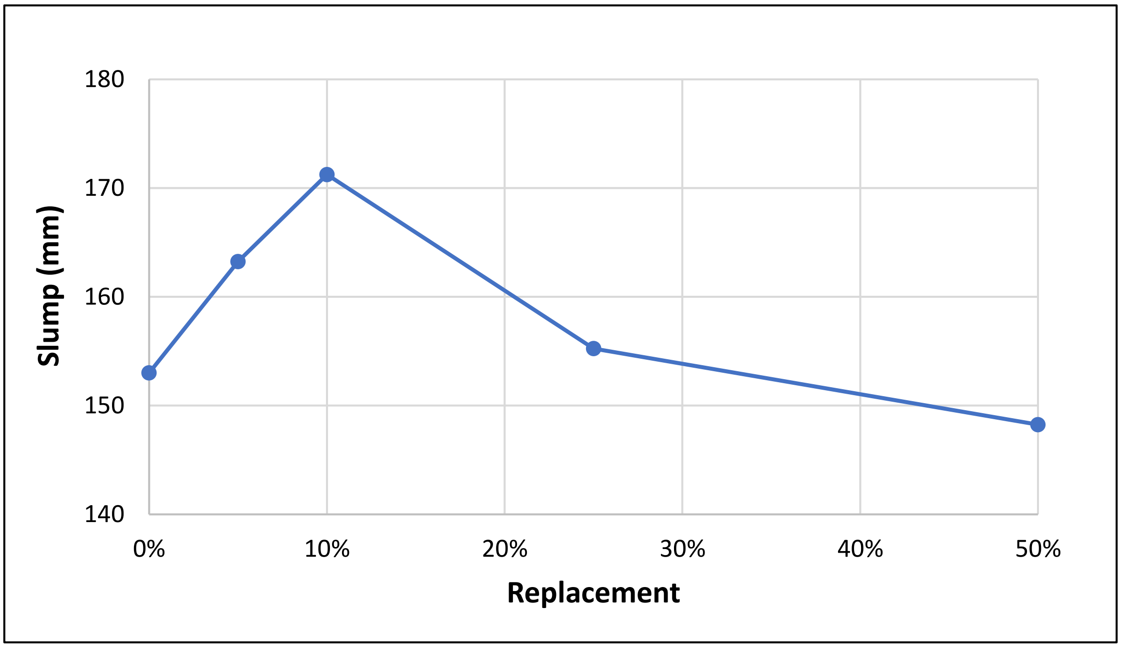


Figure 61: Spread variation (mini cone) with the increase of the replacement.

In the trend of the slump spreads produced by the mini cone (Figure 61), the values display the increase of the diameters average, therefore also of workability and flowability, up to 10% of replacement by the brick sand. While, over 10% of replacement by the brick sand, the spread of the slump decreases, until it reaches a lower value respect to the reference mortar (BS-0). The same trend is indicated by the results obtained with the MBE cone (Figure 62).

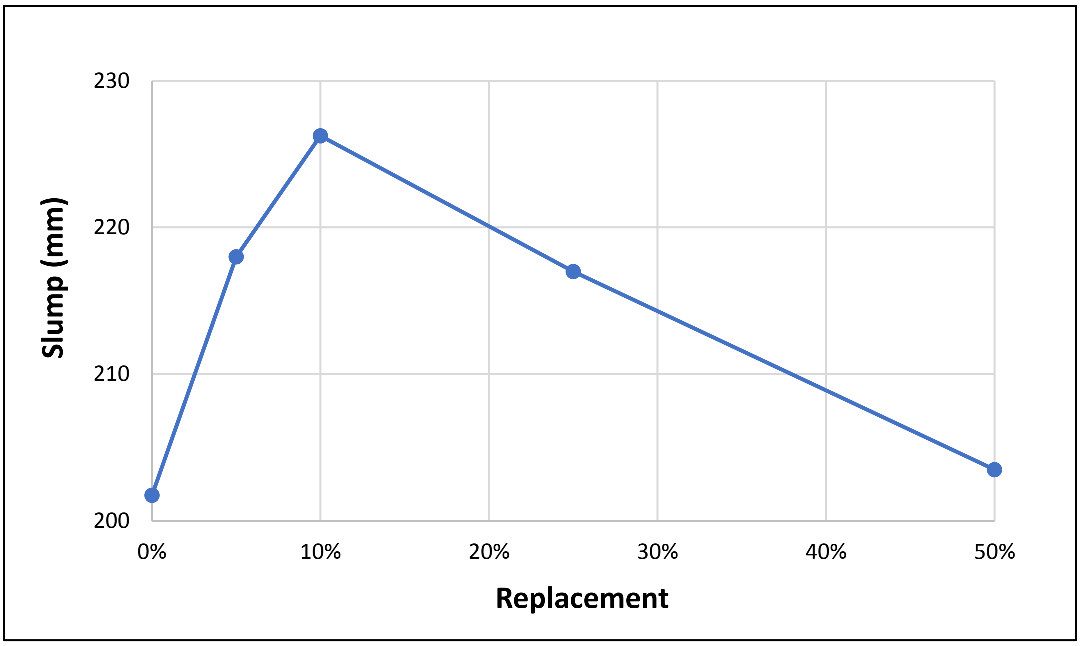


Figure 62: Spread variation (MBE cone) with the increase of the replacement.

Indeed, the spread obtained by the MBE cone indicates an increase up to the 10% of replacement and, then, a linear decrease of the value is recorded.

For each test made with the mini cone, the thickness of the spread is recorded immediately after the measuring phase of the diameters (Figure 63). This parameter is indirectly dependent on the slump test results.

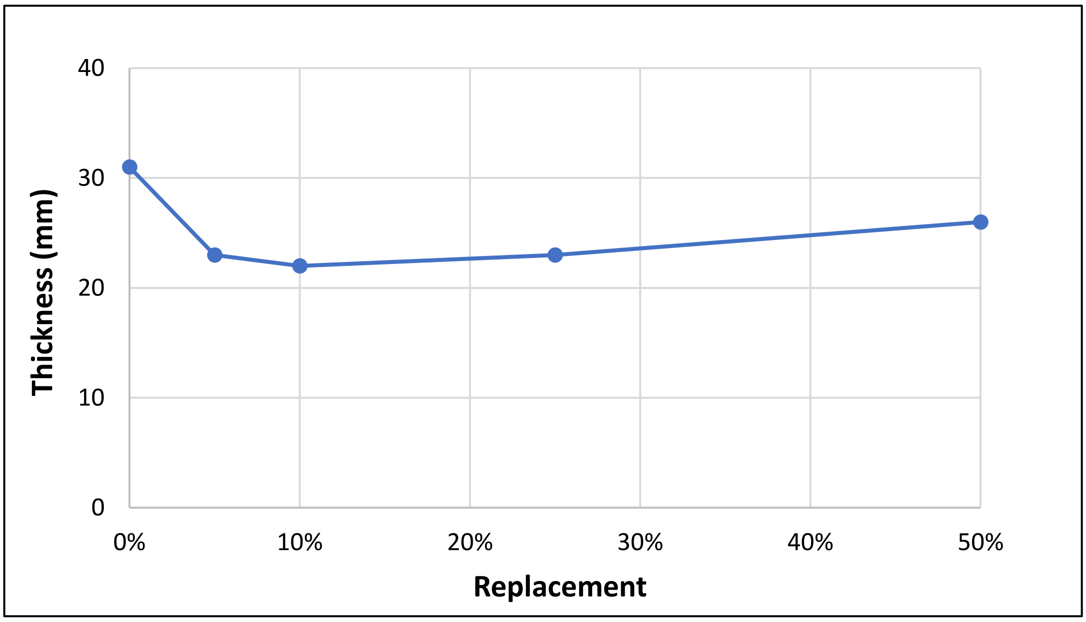


Figure 63: Thickness variation for the increase of the replacement.

The relation between the two parameters is displayed by the trend of the thickness of the spread. With the increase of the limestone sand replacement up to 10%, the thickness decreases to 22 mm. While, with 25% and 50% of replacements, the thickness starts to increase due to the decreasing of the spread produced by the slump test. These results are certainly correlated to the differences in the particles size distribution between the limestone sand and the brick sand. However, also the particles shape can influence the friction between them leading to the decrease in the flowability.

Moreover, the porosity of the brick grains leads to the absorption of the mixing water, which is greater with the increase of the sand brick percentage.

Air content test

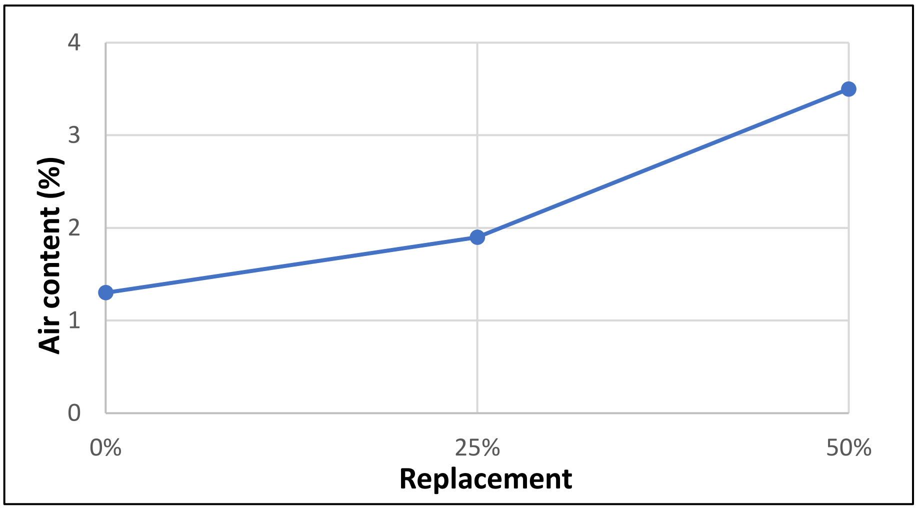


Figure 64: Air content variation for the partial limestone sand replacement.

From the characterization phase and the analysis on the absorption of the brick sand, it's clear the presence of the porosity, which is higher respect to the limestone sand. This aspect influences the fresh properties of the mortar the density and the air content. The Figure 64 exposes the trend of the air content with the increase of the brick sand. The presence of the brick sand leads to the increase of the air content inside the mortar. This behavior can be linked to two different aspects. First, the cement paste could present some inefficiency in the attachment to the brick grains generating the spaces filled by the air. Secondarily, the higher porosity of the brick sand, compared to the limestone sand, can contain still some air, even after the pre-saturation phase, which increases the final air content.

Volumetric mass analysis

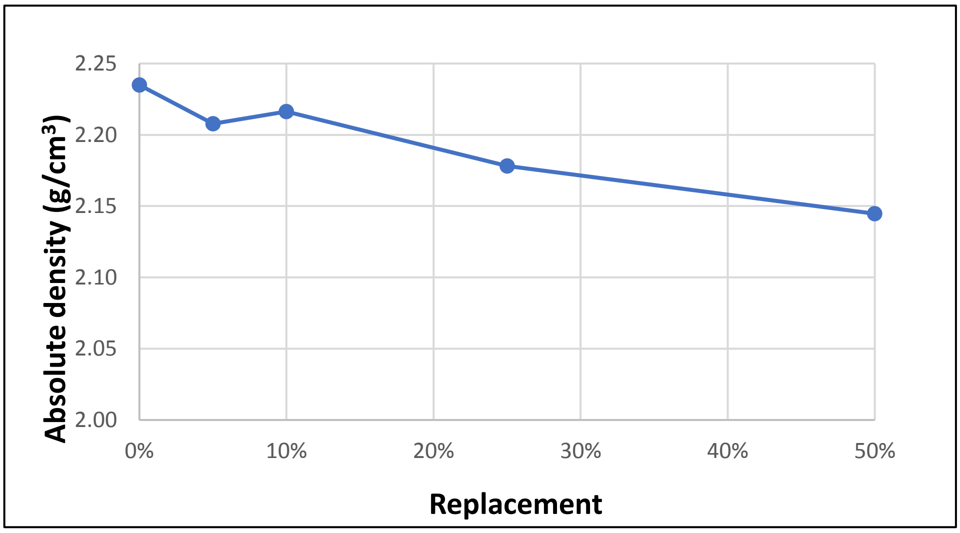


Figure 65: The volumetric mass variation for the increase of the replacement by the brick sand.

The trend of the air content is justified also by the volumetric mass variation (Figure 65). The graph indicates a gradual decrease of the final density of the mortar with the increase of the brick sand fraction inside the composition.

This behavior is linked both to the particles size distribution and to the porosity of the material. Indeed, due to larger portion of the coarser particles compared to the limestone sand, the brick sand cannot guarantee a good compactness in the mortar, leading to the decrease of the absolute density. While, the higher porosity of the brick leads to the increase of the voids filled by the air, which, due to the lower density, decrease further the absolute density.

RheoCAD analysis

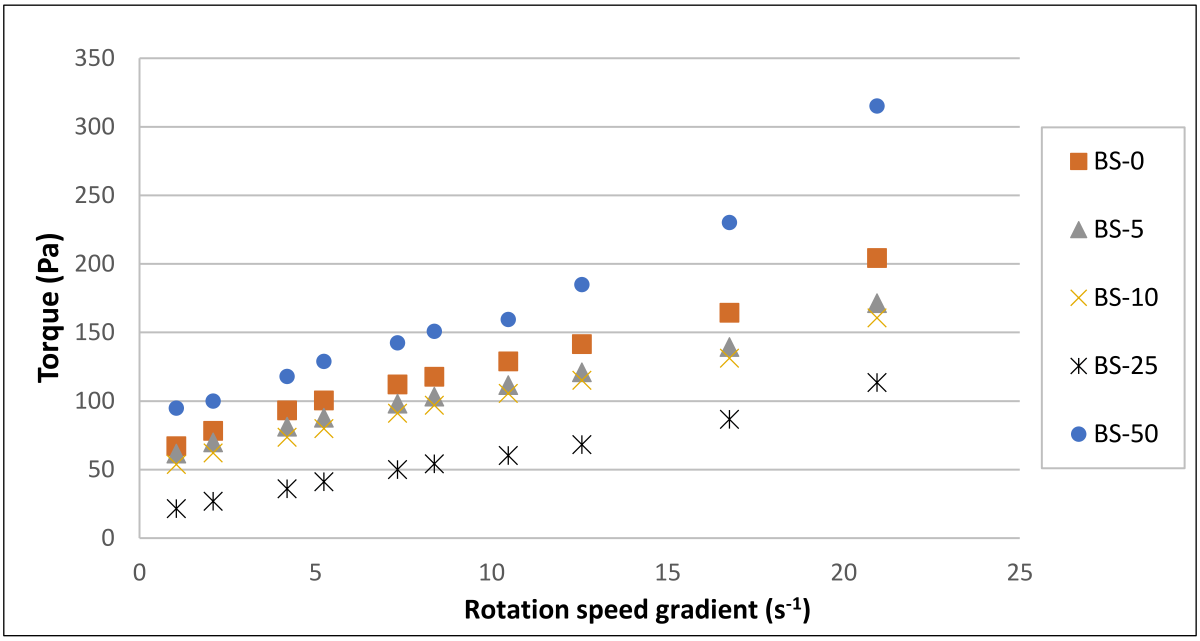


Figure 66: The torque variation in respect to the increase of the rotation speed.

The same program used for the limestone filler case is performed in this situation. In Figure 66, the variation of the torque, expressed in Pa, is depicted with the increase of the rotation speed. All the mortars reveal the linear relationship between the torque and the rotation speed. Generally, the gradient of the trendline decreases with the increase of the brick sand inside the composition. However, in the BS-50, the data presents an increase compared to other cases.

For each sample, the trendline is computed (Annex 15). Then the Bingham model is used to analyze the rheological properties of the mortars. The equations and the parameters, which correspond to the different mortars, are displayed in Table 40.

Sample	Equation	R2	τ_0	μ
BS-0	$\tau = 63.56 + 6.42\dot{\gamma}$	0.99	63.56	6.42
BS-5	$\tau = 58.44 + 5.17\dot{\gamma}$	0.99	58.44	5.17
BS-10	$\tau = 51.65 + 5.08\dot{\gamma}$	0.99	51.65	5.08
BS-25	$\tau = 16.92 + 4.36\dot{\gamma}$	0.99	16.92	4.36
BS-50	$\tau = 71.35 + 10.23\dot{\gamma}$	0.95	71.35	10.23

Table 40: Rheological properties for the mortar samples studied.

From the values displayed in the table, the differences between the mortar samples are clear. With the increase of the brick sand in the mortar, the viscosity and the torque resistant decreases gradually. This can be linked to the higher content of the water inside the composition, which leads to a better consistency and a higher workability of the mix.

However, with the BS-50 sample, the situation is different. Indeed, the resulting torque and viscosity from the *RheoCAD* test are higher respect to all the other mortar. For this reason, further analysis should be taken to investigate the rheological properties of the mortar with this specific replacement rate.

Due to the relation between the slump test and the *RheoCAD* results, the sample BS-25 presents results that are not coherent. For this reason, should be repeated the test on it to have a more understandable result. Indeed, the other cases of mortars present values of torque and viscosity more logical to the results coming from the slump test. With a brick sand addition up to the 10%, due to the higher spread seen from the slump test, both the torque and the viscosity decrease. Moreover, the lowest spread produced by the BS-50 sample from the slump test is coherent with the higher torque and viscosity recorded.

7.2.2 Hard properties

To evaluate the mechanical properties of the mortar mixes, the flexural strength and compressive strength were measured according to the European norm EN 196-1. The Table 41 displays the results coming from the first test. Concerning the period of 14 days, the results exhibit a decrease of the final strength, with a reduction of 14% between the reference mix BS-0 and the mortar BS-50. However, the situation is reversed after 28 days. Indeed, the sample BS-50 has a flexural strength 10% higher respect to the reference mix. The BS-25 sample presents a middle value between the two other cases. The table below displays the average value of the mechanical properties. While, in Annex 17 all the results from the tests are displayed.

Sample	Flexural strength at 14 days (MPa)	Flexural strength at 28 days (MPa)
BS-0	7.55	7.25
BS-25	7.35	7.48
BS-50	6.6	8.03

Table 41: Flexural strength values at 14 and 28 days for the sand substitution case.

The same time steps were fixed for the analysis of the compressive strength. The Table 42 displays the variation of the results according to the partial replacement of the limestone sand. In both the time steps, the compressive strength increases with the increase of the brick sand inside the mortar. Indeed, concerning the 14 days step, the BS-50 has a compressive strength 11% higher compared to the reference mix BS-0. For the 28 days step, the difference increases further, reaching the 25% of discrepancy.

However, from the result of the BS-25 sample, the compressive strength decreases with the passing of the days. This behavior is unusual for the self-compacting mortar. In fact, the compressive strength tends, generally, to increase thanks to the gradual hydration process of the cement paste. For this reason, it should be reasonable to repeat the production of the sample BS-25, in order to obtain a more representative result.

Sample	Compressive strength at 14 days (MPa)	Compressive strength at 28 days (MPa)
BS-0	32.2	32.8
BS-25	32.6	31.6
BS-50	36	41

Table 42: Compressive strength at 14 and 28 days for the sand substitution case.

8. Discussion of the results

The wasted red brick materials analyzed in the present investigation presented differences in the values of the volumetric mass. The brick filler was studied through the helium, as did for the limestone filler, and the glass pycnometer. The volumetric mass that resulted using the helium pycnometer test was higher than that obtained through the brick filler. Concerning the sandy materials, on the other hand, the steel pycnometers presented results with a good and satisfactory similarity, with a low standard deviation (1%).

The next investigation was the water absorption test. Due to the inconsistency of the results produced by the standard test, based on the European norm EN 1097-6, the analysis was performed only through the IFSTTAR method. The water absorption was measured on its coarser and sand shapes, respectively at 11.3% and 15.1% The difference recorded between the two kinds of samples is linked to the overestimation of the water absorption for the brick sand. Indeed, when the agglomeration between the grains takes place, it leads to an increase of the water still inside the material. However, comparing the results with the value obtained for the limestone sand (0.84%), the difference presents a higher absorption by the brick sand. The higher porosity of the brick sand is the main cause of this relevant difference.

Continuing with the characterization of the materials, the granulometric analysis was performed to compare the particles size distributions. For the filler materials, the analysis was carried out through the laser diffraction. It resulted that the brick filler had a coarser distribution of the sizes compared to the limestone filler. Moreover, the granulometric curve displayed a monodisperse trend. Differently to the filler materials, the sandy samples were analyzed through the classic vibratory sieves. The brick sand, also in this case, showed a coarser distribution of the particles size compared to the limestone sand, with a monodisperse granulometric distribution. These differences of granulometric distribution and of water absorption were confirmed with the analysis on the mortar samples produced. Indeed, a general rule is that the physical properties of the materials might affect the results.

The analysis of the rheological properties for several mixes, through the RheoCAD, demonstrated the good suitability of the Bingham model to measure the viscosity of the mortars. The measured rheological properties confirmed the results obtained by the analysis of the fresh properties of several mortar samples. However, some of the rheological test should be repeated in order to achieve a more satisfactory analysis.

The analysis on the mechanical properties of the mortars confirmed the impact of the recycled bricks on the final compressive and flexural strength. The mechanical properties after 7 days, with the partial substitution of the limestone filler did not presented any correlation between the brick filler quantity and the water content. However, the increase of the brick filler, both for the BFWA and the BFNWA samples, from 50% to 100% in volume of the limestone filler, brought to the worsening of the mechanical properties. At 28 days, the BFWA samples record a decrease of the compressive strength with the rise of the brick filler inside. While the BFNWA samples outlined a surge of the compressive strength with the increase of the brick filler presence.

A similar trend emerged from the analysis of the partial substitution of the limestone sand with brick sand. The mechanical properties showed an improvement of the compressive strength and of the flexural strength with a higher brick sand content into the mortar. This trend is not usual. However, even if with a simple vibrated mortar, *Zhang et al.*, during their investigations on the mechanical properties variation with the use of clay bricks recorded an improvement of the compressive strength at 28 days [88].

9. Conclusions

The constantly growth of the world population will not decelerate the development of bigger cities, where the demand of new buildings is the main purpose of the construction sector. For this reason, the construction industry will represent the first consumer of raw materials and will remain one of the main greenhouse gases producer One of the most effective way to reduce its impact is the transformation of its wastes into resources to be re-use in industrial processes.

The investigations performed during the present work wanted to point out the potentiality of the re-use of a recycled filler and sand from crushed bricks for the production of the self-compacting mortar. The study was based on the comparison of the physical and mechanical properties of mortars obtained by mixing traditional and recycled materials: what is the impact of the gradual replacement of the limestone filler and the limestone sand with waste bricks' filler and sand. More specifically, the waste bricks were first treated and prepared for obtaining suitable and similar physical properties to those of traditional materials that had to be substituted.

The characterization of the brick filler and the brick sand showed several differences compared to the limestone fractions. The absolute density of the recycled bricks had a similar value of the natural filler and the natural sand, while the water absorption coefficient was greater. Granulometry of waste bricks filler and waste bricks sand was coarser, even after two grinding processes.

After the characterization of the materials, the investigation on the mortars was divided into two different phases: the gradual replacement of the limestone filler, first, and, subsequently, the replacement of limestone sand with the ground waste bricks having similar granulometry range. For each case study, the fresh and the mechanical properties were investigated. The results demonstrated the considerable variations caused by the waste bricks fractions.

In the case of the limestone filler substitution by the waste brick filler (BFNWA samples), the mortar presents an increase of the absolute density and of the air content, together with a reduction of workability, which is probably due to the high hydrophilicity of the bricks. The BFWA samples, where it was considered the possible influence of the waste bricks on the water content, produced further differences. The addition of water to compensate the possible absorption reduced the absolute density, but allowed the achievement of a better workability. This is due to the higher water content inside the mortar with the waste bricks compared to the reference mix which reduces the friction between grains. The measurement of the absolute density and the air content demonstrated this relationship between water content and volumetric mass.

The mechanical properties at 7 days did not present a clear correlation between the brick filler and the water content. However, the compressive strength showed a general worsening with the increase of the brick filler content, while, the compressive strength at 28 days showed an improvement of values in the BFNWA samples with lower water content.

Thus, water is more affecting longer-term mechanical properties than shorter ones. Consequently, further investigations should be carried out to better understand the possible relationship between water and the brick filler inside the self-compacting mortar.

In the case of the limestone sand substitution with waste brick sand, a similar behavior emerged. The physical differences between the recycled and the natural material were measured during the granulometry analysis and during the water absorption tests. These differences were demonstrated by the analysis on the fresh and rheological properties of the mortar samples. Indeed, the increase of the brick sand content inside the self-compacting mortar reduced the workability of the mixes.

Although the material was pre-saturated before the tests, the higher water content inside the mortar did not led to the improvement of the workability. The higher porosity of the bricks was confirmed by the air content test and by the analysis of the volumetric masses: the air content of the mortars has indeed increased with the increase of the brick sand content, while the absolute density decreased with the rise of the brick sand replacement inside the composition. The mechanical properties measured at 14 and 28 days presented an increase both of the flexural strength and of the compressive strength with a rise of the brick sand content in the mortar samples. This behavior is not so usual. Indeed, due to the higher air content and the lower absolute density caused by the waste brick sand addition, the mechanical properties should be worse than those of the reference mortar. For this reason, additional investigations should be taken to further understand the influence of the pre-saturated brick sand on the mechanical properties of the self-compacting mortar.

These results were obtained by studying some particular waste bricks. However, as already explained in Chapter 1, the main problem of wastes coming from demolitions, as well as from constructions, is the heterogeneity of their composition. Moreover, the recycling choices of C&DW is usually correlated to the variability and the type of the wastes together with their treatments processes, which are performed to ensure wastes with better properties that allow an easier and more effective reuse. Therefore, it is suggested to repeat the same study on other kind of clay waste bricks, in order to obtain a sufficiently number of analysis to perform a comparison between different recycled materials. Thanks to this, a more detailed knowledge of the physical and mechanical properties of the self-compacting mortar and the self-compacting concrete will guarantee the general application of this recycled materials.

Further analysis should be carried out to investigate the economic impact of the recycled materials addition on the total cost for a given volume of concrete, compared to the traditional compositions. In this way, it’s possible to evaluate more clearly the recycling of the construction wastes, such as the bricks, in all their aspects.

However, the results obtained from the present analysis are promising.

Annexes

Annex 1: Technical document of the bricks

ploegsteert
The new building tradition.

Bloc haute résistance / Hoge weerstandsblok 288 x 138 x 138

CE 2+
0749
06

Déclaration des Performances	**Prestatieverklaring**	**DoP_HB780_20160101**
Type de produit	Producttype	Bloc haute résistance / Hoge weerstandsblok
Usage prévu	Beoogd gebruik	Briques HD pour maçonnerie non-protégée dans murs, poteaux et cloisons en maçonnerie. / HD metselstenen voor onbeschermd metselwerk in metselwerkmuren, kolommen en scheidingswanden.
Nom du fabricant	Naam fabrikant	SA Briqueteries de / Steenbakkerijen van **Ploegsteert** nv · Touquetstraat 228 · 7782 Ploegsteert **Division Barry** · Grand Route 533 · 7534 Barry
Organisme notifié	Certificierende instantie	BCCA (n° NB 0749) : Inspection initiale de l'établissement de fabrication et du contrôle de la production en usine ; Surveillance, évaluation et appréciation permanentes du contrôle de la production en usine ; Livraison du certificat de conformité du contrôle de la production en usine. / Initiële inspectie van productie-installatie en productiecontrole in de fabriek; Permanente bewaking, beoordeling en evaluatie van de productiecontrole in de fabriek; Verstrekt conformiteitscertificaat van productiecontrole in de fabriek.

Performances déclarées	Verklaarde prestaties	(selon/volgens NBN EN 771-1:2011)			
Dimensions	Afmetingen	Longueur Largeur Hauteur	Lengte Breedte Hoogte	mm mm mm	288 138 138
Tolérances dimensionelles	Tolerantie				T2
Plage	Maatspreiding				R2
Planéité des faces de pose	Vlakheid legvlakken			%	1
Parallélisme des faces de pose	Parallelisme van legvlakken				2
Configuration	Verschijningsvorm	Brique à perforation verticale Pourcentage des vides	Verticaal geperforeerd product Percentage holle ruimtes	 %	Groupe 2 <50
Masse volumique apparente sèche	Bruto volumieke massa			kg/m³	1150-D2
Masse volumique absolue sèche	Netto droge volumemassa			kg/m³	2000-D1
Résistance à la compression	Druksterkte	Rés. Moy. ⊥ à la face de pose Facteur de forme / format Rés. norm. ⊥ à la face de pose Catégorie	Gem. drukst. ⊥ op mortelbedvlak Vormfactor / formaat Genorm. drukst. ⊥ op mortelbedvlak Categorie	N/mm² N/mm² 	≥ 35 1.1 38 I
Dilatation due à l'humidité	Vochtexpansie			mm/m	NPD
Adhérence mortier d'usage mince	Hechtsterkte verlijmd	Valeurs fixes tabl. EN998-2 ann C	Tabelwaarden EN998-2 ann C	N/mm²	NPD
Adhérence mortier d'usage courant	Hechtsterkte vermetseld	Valeurs fixes tabl. EN998-2 ann C	Tabelwaarden EN998-2 ann C	N/mm²	NPD
Teneur en sels solubles actifs	Gehalte actieve oplosbare zouten	Classe	Klasse		S2
Réaction au feu	Brandreactie	Classe	Klasse		A1
Absorption d'eau	Wateropneming			%	≤12
Taux initial d'absorption d'eau	Initiële wateropzuiging	Classe	Klasse	kg/m².min	1,5 < IW ≤ 4,0
Propriétés thermiques	Thermische eigenschappen	$\lambda_{10, sec, unité}$	$\lambda_{10, droog, steen}$	W/m.K	0.28
Durabilité contre gel/dégel : résistance au (dé)gel	Duurzaamheid inzake vriezen en dooien				F2
Substances dangereuses	Gevaarlijke stoffen				NPD
Perméabilité à la vapeur d'eau	Dampdoorlatendheid	Valeur min. et max. (EN1745, tableau 1)	Min. en max. waarde (EN1745 Tabel 1)		05/10

Les performances du produit identifié sont conformes aux performances déclarées dans le tableau ci-dessus. Signé pour le fabricant et en son nom par Karel Rommel, directeur commercial briques, à Ploegsteert.

De prestaties van het hierboven omschreven product zijn conform de verklaarde prestaties. Deze prestatieverklaring werd ondertekend voor en namens de fabrikant door Karel Rommel, commercieel directeur stenen, te Ploegsteert.

Date / Datum 20160101

Propriétés techniques nationales supplémentaires / Aanvullende nationale specificaties (Selon / Volgens BB/202/681/024-00-P/01)

Résistance au gel/dégel	Vorst/Dooi weerstand	Selon / Volgens NBN B 27-009	Résistance élevée au gel
Propriétés thermiques $\lambda_{10, sec, unité}$ (90/90)	Thermische eigenschappen $\lambda_{10, droog, steen}$ (90/90)	W/m.K	0.32
Efflorescence	Neiging tot uitbloeiing	Selon / Volgens NBN B 24-209	Pas d'efflorescence

BENOR

Avis au client au verso/ Bericht aan de klant op keerzijde.

Bloc haute résistance / Hoge weerstandsblok **288 x 138 x 138**

HB780

Annex 2: Description of the jaw crushers

DOC-17-O-11 : Fiche présentation équipement   Rev : 0

Catégorie	***Préparation mécanique***
Sous-Catégorie	***Concassage***
Opération	***Continu***
Utilisation	***Fragmentation par écrasement***

member of FMRA

Concasseur à mâchoires — D003

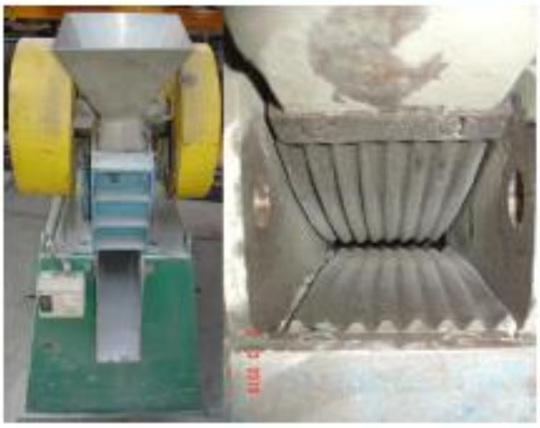
Type	120
Principe fonctionnel	Fragmentation par écrasement entre 2 mâchoires, l'une fixe, l'autre mobile
Matériaux	durs et abrasifs
Capacité	100-200 kg/h
Input	0 / 80 mm
Output	0 / 10 mm
Puissance motrice (kW)	2,75

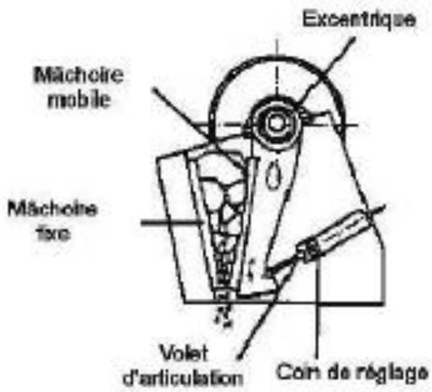
Caractéristiques

- Ouverture inférieure position fermée de dent à creux : Min 5mm / Max 32mm
- Dim. Mâchoires : L=220mm, l=120mm

Exploitant un mode de fragmentation par compression et écrasement, l'appareil est constitué de 2 mâchoires (plaques dentées) disposées face à face en forme de V. Une plaque est fixe, l'autre mobile et animée d'un mouvement oscillant par le jeu d'un système bielle-excentrique. La compression est produite lors du mouvement de la mâchoire mobile vers la mâchoire fixe et provoque l'éclatement des gros blocs du matériau introduit à la partie supérieure du concasseur. L'éloignement de la mâchoire mobile permet à ceux-ci de descendre dans la machine, où ils subissent encore plusieurs réductions successives de taille avant d'être déchargés à sa partie inférieure.

L'appareil est typiquement utilisé pour effectuer la première fragmentation du matériau à traiter (tout-venant), lequel peut comporter des blocs très volumineux (concassage primaire).





CTP member of FMRA

Catégorie	***Préparation mécanique***
Sous-Catégorie	***Concassage***
Opération	***Continu***
Utilisation	***Fragmentation par écrasement***

Concasseur à mâchoires

D004

Type	220
Principe fonctionnel	Fragmentation par écrasement entre 2 mâchoires, l'une fixe, l'autre mobile
Matériaux	Mi-durs et durs (dureté Mohs < 8,5)
Capacité	1 t/h
Input	0 / 200 mm
Output	0 / 30 mm
Puissance motrice (kW)	11

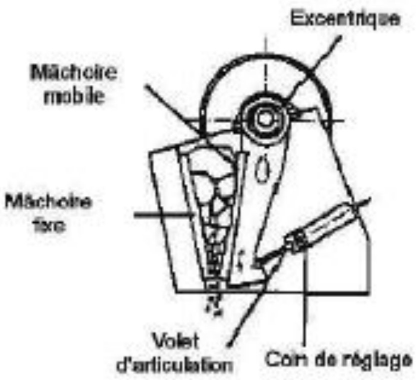
Caractéristiques

- Ouverture inférieure position fermée de dent à dent : Min 10mm / Max 50mm
- Hauteur denture : 15 mm
- Dim. Mâchoires : larg. 220mm / long. 440mm

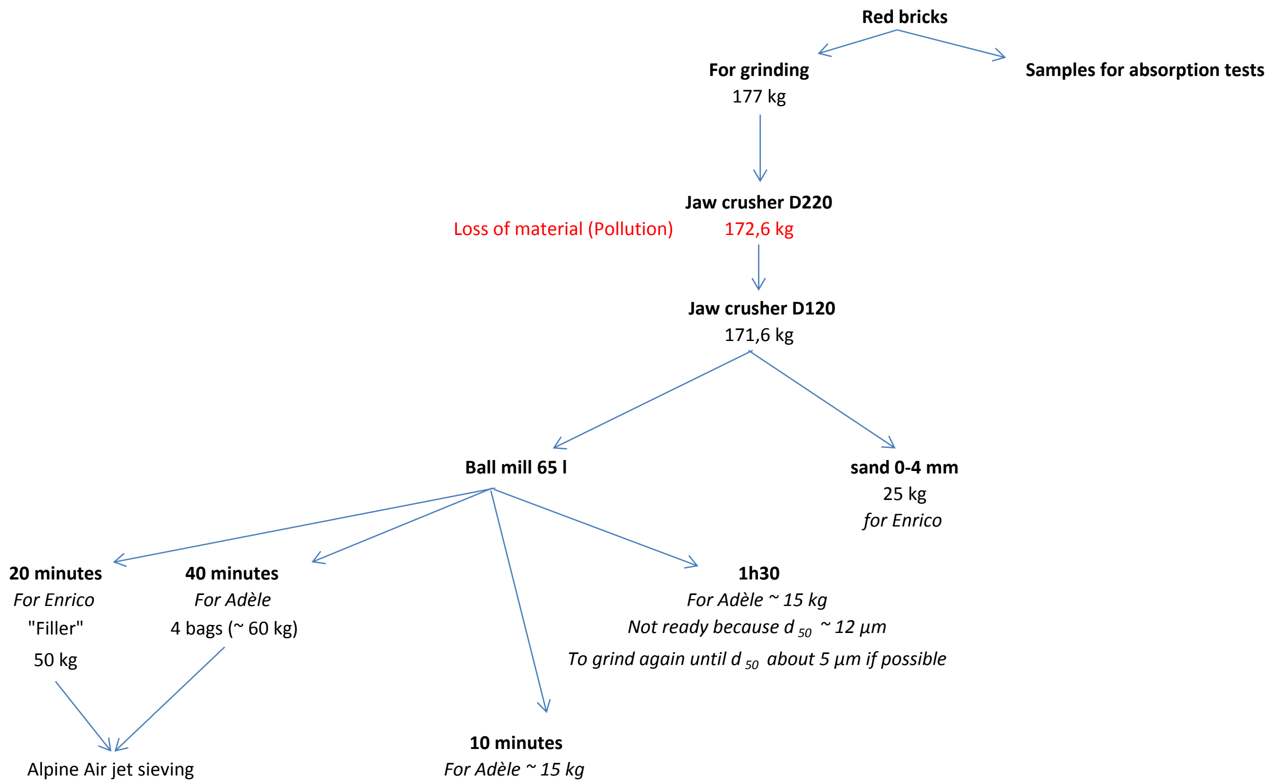
Exploitant un mode de fragmentation par compression et écrasement, l'appareil est constitué de 2 mâchoires (plaques dentées) disposées face à face en forme de V. Une plaque est fixe, l'autre mobile et animée d'un mouvement oscillant par le jeu d'un système bielle-excentrique. La compression est produite lors du mouvement de la mâchoire mobile vers la mâchoire fixe et provoque l'éclatement des gros blocs du matériau introduit à la partie supérieure du concasseur. L'éloignement de la mâchoire mobile permet à ceux-ci de descendre dans la machine, où ils subissent encore plusieurs réductions successives de taille avant d'être déchargés à sa partie inférieure.

Le rapport de réduction est de l'ordre de 4 : 1.

L'appareil est typiquement utilisé pour effectuer la première fragmentation du matériau à traiter (tout-venant), lequel peut comporter des blocs très volumineux (concassage primaire).



Annex 3: Flowsheet for the bricks treatment



Annex 4: Cement's properties and parameters

Ciment Portland

CEM I 52,5 N

CEM I

Février 2017

CEM I 52,5 N

1. Normes et certificats

Désignation	Marque	Norme	Certificat N°
CEM I 52,5 N CE	CE	NBN EN 197-1	0965-CPR-C0019
CEM I 52,5 N CE BENOR	BENOR	NBN B12	17/02/019
CEM I 52,5 N CE	KOMO	BRL 2601	1118-16-1020

2. Composition déclarée

	Unité	Méthode d'essai	Valeurs moyennes	Exigences Min	Exigences Max
Constituants en % de la somme des constituants principaux et secondaires					
Clinker (K)	%	-	97	95	100
Laitier (S)	%	-	-	-	-
Cendres volantes (V)	%	-	-	-	-
Calcaire (LL)	%	-	-	-	-
Filler	%	-	3	0	5
Ajouts en % du ciment fini					
Régulateur de prise	%	-	5	-	-
Agent de mouture	%	-	0.14	-	-
Agent réducteur *	%	-	0.5	-	-

* Conformément au Règlement CE 1907/2006 (Reach), un agent réducteur est ajouté à certains ciments afin de limiter la teneur en chrome (VI) soluble à 0,0002% maximum.

3. Caractéristiques chimiques et minéralogiques

	Unité	Méthode d'essai	Valeurs moyennes	Exigences Min	Exigences Max
CaO	%	EN 196-2	63.4	-	-
SiO_2	%	EN 196-2	20.4	-	-
Al_2O_3	%	EN 196-2	4.8	-	-
Fe_2O_3	%	EN 196-2	3.4	-	-
C_3A	%	EN 196-2	7.2	-	-
SO_3	%	EN 196-2	3.2	-	≤ 4.0
Résidu insoluble	%	EN 196-2	0.6	-	≤ 5.0
Perte au feu	%	EN 196-2	1.6	-	≤ 5.0
Chlorures	%	EN 196-2	0.08	-	≤ 0.10
Chrome (VI) *	%	EN 196-10	< 0.0002	-	≤ 0.0002
Na_2Oeq**	%	EN 196-2	0.74	-	-
Sulfures	%	EN 196-2	-	-	-

* Conformément au Règlement CE 1907/2006 (Reach), la teneur en chrome (VI) soluble est limitée à 0,0002 % maximum.

** Valeur moyenne + 1,96 x écart-type.

Cimenteries CBR
Assistance Technique
Chaussée de La Hulpe 185 Terhulpsesteenweg
1170 Bruxelles
Tel : + 32 2 678 35 10
Fax : + 32 2 675 23 91
communication@cbr.be
www.cbr.be

ENCI
Assistance Technique
Postbus 3233
5203 DE 's-Hertogenbosch
Tel : + 31 73 640 12 20
Fax : + 31 73 640 12 18
tv@enci.nl
www.enci.nl

Usine de Lixhe

4. Caractéristiques physiques

	Unité	Méthode d'essai	Valeurs moyennes	Exigences	
				Min	Max
Blancheur	%	CIE 1931	0	-	-
Clarté L	%	CIE Lab	59	-	-
Eau de consistance normale	%	EN 196-3	29.6	-	-
Début de prise	min	EN 196-3	200	≥ 45	-
Fin de prise	min	EN 196-3	260	-	≤ 720
Stabilité	mm	EN 196-3	<1	-	≤ 10
Surface spécifique (Blaine)	cm²/g	EN 196-6	3800	-	-
Refus au tamis de 200 µm	%	EN 196-6	0.02	-	≤ 3.0
Chaleur d'hydratation à 7 jours	J/g	EN 196-8	-	-	-
Masse volumique - Absolue	kg/m³	-	3100	-	-
Masse volumique - Apparente	kg/m³	-	1100	-	-

5. Caractéristiques mécaniques

	Unité	Méthode d'essai	Valeurs moyennes	Exigences	
				Min	Max
A 1 jour	MPa	EN 196-1	20.5	-	-
A 2 jours	MPa	EN 196-1	37	≥ 20	-
A 7 jours	MPa	EN 196-1	55	-	-
A 28 jours	MPa	EN 196-1	66.5	≥ 52.5	-
2d/28d	-	-	0.56	-	-

6. Production et conditionnement

Ce ciment est disponible dans les conditionnements suivants :

Vrac bateau	Vrac camion	Sac
X	X	X

7. Système de management certifié de l'usine.

8. Déclaration de performance

Déclaration de performance CPR(EU) Nr. 305/2011

Identification : 0965-CPR-C0019

Site internet : www.cbr.be

Les valeurs reprises ci-dessus sont des valeurs moyennes qui sont données à titre indicatif.

Les limites garanties figurent dans la colonne exigences.

Annex 5: Limestone filler properties

CARMEUSE
NATURAL CHEMICALS

FICHE TECHNIQUE

CALCITEC 2001S

FILLER CALCAIRE – $CaCO_3$

ANALYSE CHIMIQUE TYPE (valeurs moyennes sur sec)

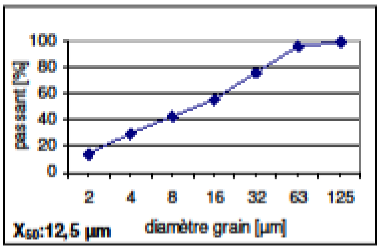
	Exigence absolue BRL 1804	Exigence BRL 1804	Exigence suivie 90%	Moyenne
Carbonate	≥ 87	≥ 90	94-100	98,8 %
$CaCO_3$	≥ 72	≥ 75	94-100	98,1 %
MgO				0,31 %
SiO_2				0,60 %
Al_2O_3				0,16 %
Fe_2O_3				0,08 %

Réactivité aux alcalins	non réactif
$Na_2O_{éq} = Na_2O + 0{,}658 \times K_2O$	0,03 %
Teneur en eau	0,12 %
Soufre total (S)	0,04 %
Sulfates solubles dans l'acide (SO_3)	0,1 %
Ions chlorures solubles dans l'eau (Cl^-)	< 0,008 %
Matières organiques	pas de M.O.
pH	9,5

CARACTERISTIQUES PHYSIQUES & DISTRIBUTION GRANULOMETRIQUE (valeurs moyennes)

CALCAIRE VISEEN	
Masse volumique réelle	2.700 kg/m³
Densité apparente non tassé	1.000 kg/m³
Densité apparente tassé	1.500 kg/m³
Surface spécifique Blaine	350 m²/kg
Surface spécifique BET	1,0 m²/kg
Valeur au bleu MB	0.66 %
Blancheur FY	53
Dureté (Mohs)	3

DISTRIBUTION GRANULOMETRIQUE
Courbe granulométrique laser SYMPATEC



Passant au tamis de	Exigence individuelle % m/m	Intervalle 90% % m/m	Moyenne % m/m
2 mm	100	100	100
500 µm	-	99 - 100	99,9
125 µm	85 - 100	90 - 100	97
63 µm	70 - 100	74 - 84	78

LIEU DE PRODUCTION
B - 4480 ENGIS

SECURITE
Fiche de sécurité disponible sur demande.
Le produit est inerte et non dangereux

STOCKAGE
Stocker à l'abri de l'humidité.

REF/NORMES
EINECS 215-279-6
CAS 471-34-1
Exempté de REACH
0785-CPR-31-214-13
04
EN 12620
EN 13139
DoP: 0785-CPR-31-214-04-En-42-1306

CE
0785

Le produit étant d'origine naturelle, les valeurs mentionnées peuvent être sujettes à des variations et n'engagent nullement la société

MISE A JOUR 13/06/2014 N°EDITION 20.55.216b CARMEUSE SA www.carmeuse.be info@carmeuse.be

Annex 6: Granulometric analysis results for the brick sand

Specimen-1			
Sieve opening (mm)	**Mass total (g)**	**Refuse (%)**	**Passing (%)**
4	2.94	1%	99%
2	115.32	39%	61%
1	73.74	64%	36%
0.5	36.71	76%	24%
0.25	15.77	81%	19%
0.125	9.38	85%	15%
0.063	9.73	88%	12%
0	36.94	100%	0%

Specimen-2			
Sieve opening (mm)	**Mass total (g)**	**Refuse (%)**	**Passing (%)**
4	2.35	1%	99%
2	99.45	34%	66%
1	66.13	56%	44%
0.5	40.2	69%	31%
0.25	19.77	76%	24%
0.125	12.49	80%	20%
0.063	14.66	85%	15%
0	44.15	100%	0%

Specimen-3			
Sieve opening (mm)	**Mass total (g)**	**Refuse (%)**	**Passing (%)**
4	2.05	1%	99%
2	115.11	39%	61%
1	71.8	63%	37%
0.5	36.94	75%	25%
0.25	15.94	81%	19%
0.125	9.8	84%	16%
0.063	11.28	88%	12%
0	36.54	100%	0%

Annex 7: Physical properties for the normalized sand (EN 196-1)

SNL

Société Nouvelle du Littoral

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SABLE NORMALISE CEN CERTIFIE CONFORME – EN 196.1 par l'AFNOR et conforme ISO 679

Contrôlé par le Laboratoire d'Essais des Matériaux de la Ville de Paris (L.E.M.V.P.)
4 Avenue du Colonel Henri Rol-Tanguy
75014 PARIS

Fabrication Sable Normalisé CEN, conforme EN 196-1

	Date mesure	Valeur ponctuelle	Valeur min	Valeur max
Masse volumique réèlle (Mg/m3) EN 1097-6	novembre-11	2,64		
Absorption eau (%) EN 1097-6	novembre-11	0,2		
Module de finesse (%) EN 12620	novembre-11		2,6	2,7
Ecoulement sable (s) EN 933-6	novembre-11	28		
Teneur en eau (%)	janvier-17		0,02	0,07
	février-17		0,01	0,07
	mars-17		0,03	0,07
Teneur en chlorure (ppm)	janvier-17		< 50	
	février-17		< 50	
	mars-17		< 50	
Teneur en silice (% SiO2)	janvier-16	98,05		
Teneur alumine (% Al2O3) ISO 29581-2	janvier-16	0,54		
Teneur fer (% Fe2O3) ISO 29581-2	janvier-16	0,07		
Perte au feu 950 °C (EN 196-2)	janvier-16	0,16		
teneur P2O5 % ISO 29581-2	janvier-16	0		

S.N.L. fondée en 1910 – SAS capital 250 000 € - NIF FR 93 976 750 257 – SIRET 976 750 257 00025 APE 0812Z
Certifiée pour la PREPARATION DU SABLE NORMALISE CEN POUR LA DETERMINATION DES RESISTANCES MECANIQUES DES CIMENTS
FR C3 - MAJ 04/12-

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Fabrication Sable Normalisé CEN, conforme EN 196-1

	Date mesure	Valeur ponctuelle	Valeur min	Valeur max
Masse volumique rèèlle (Mg/m3) EN 1097-6	novembre-11	2,64		
Absorption eau (%) EN 1097-6	novembre-11	0,2		
Module de finesse (%) EN 12620	novembre-11		2,6	2,7
Ecoulement sable (s) EN 933-6	novembre-11	28		
Teneur en eau (%)	janvier-17		0,02	0,07
	février-17		0,01	0,07
	mars-17		0,03	0,07
Teneur en chlorure (ppm)	janvier-17		< 50	
	février-17		< 50	
	mars-17		< 50	
Teneur en silice (% SiO2)	janvier-16	98,05		
Teneur alumine (% Al2O3) ISO 29581-2	janvier-16	0,54		
Teneur fer (% Fe2O3) ISO 29581-2	janvier-16	0,07		
Perte au feu 950 °C (EN 196-2)	janvier-16	0,16		
teneur P2O5 % ISO 29581-2	janvier-16	0		

Annex 8: Volumetric mass results for the brick filler

Bricks Filler- Stainless-steel Pycnometer								
Pycnometer n°	Pycnometer mass (g)	P+F mass (g)	P+F+W mass (g)	P+W mass (g)	Density water (g/cm^3)	Filler mass (g)	Filler volume (g/cm^3)	Absolute density filler (g/cm^3)
1	45.00	57.73	153.66	145.33	1	12.74	4.42	2.88
2	45.20	59.87	154.08	145.17	1	14.67	5.78	2.54
3	45.37	59.41	154.03	144.90	1	14.04	4.92	2.85
4	45.37	57.35	152.94	144.30	1	11.98	3.34	3.58
5	45.04	59.60	153.66	144.28	1	14.56	5.19	2.81
6	45.30	56.49	152.41	145.06	1	11.19	3.85	2.90

P=Pycnometer; F=Filler; W=Water.

Helium Pycnometer	
Pycnometer	Absolute density (g/cm^3)
1	3.04
2	3.09
3	3.09

Annex 9: Results from the β-p test

Brick filler								
Sample	Water (g)	Volume filler (cm^3)	w/p	Absolute density (g/cm^3)	Mass (g)	Diameter 1 (mm)	Diameter 2 (mm)	Relative flow area
1	300	200	1.5	3.0741	614.82	267.50	267.50	6
2	275	225	1.2	3.0741	691.67	173.24	173.24	2
3	280	220	1.3	3.0741	676.30	196.85	196.85	3
4	270	230	1.2	3.0741	707.04	137.25	137.25	1
5	285	215	1.3	3.0741	660.93	234.50	234.50	4
6	290	210	1.4	3.0741	645.56	252.75	252.75	5

Limestone filler								
Sample	Water (g)	Volume filler (cm^3)	w/p	Absolute density (g/cm^3)	Mass (g)	Diameter 1 (mm)	Diameter 2 (mm)	Relative flow area
1	230.68	269.32	0.86	2.71	729.86	190.34	195.86	2.7
2	240	260	0.92	2.71	704.60	219.11	212.56	3.7
3	250	250	1.00	2.71	677.50	283.40	288	7.2
4	220	280	0.79	2.71	758.80	168.56	169.42	1.9
5	220	280	0.79	2.71	758.80	-	-	1.5
6	230	270	0.85	2.71	731.70	-	-	2.7
7	235	265	0.89	2.71	718.15	-	-	4.3

Annex 10: Volumetric mass results for the brick sand

Bricks Sand – Stainless-steel pycnometers								
Pycnometer n°	Pycnometer mass (g)	P+S mass (g)	P+S+W mass (g)	P+W mass (g)	Density water (g/cm³)	Sand mass (g)	Sand volume (g/cm³)	Absolute density Sand (g/cm³)
18	1132.84	1390.79	1793.01	1630.21	1	257.95	95.40	2.70
8	1116.91	1397.35	1787.94	1614.53	1	280.44	107.31	2.61
19	1135.12	1413.12	1803.92	1630.88	1	278.00	105.24	2.64
13	1118.59	1420.76	1804.48	1613.19	1	302.17	111.17	2.72

P=Pycnometer; S=Sand; W=Water.

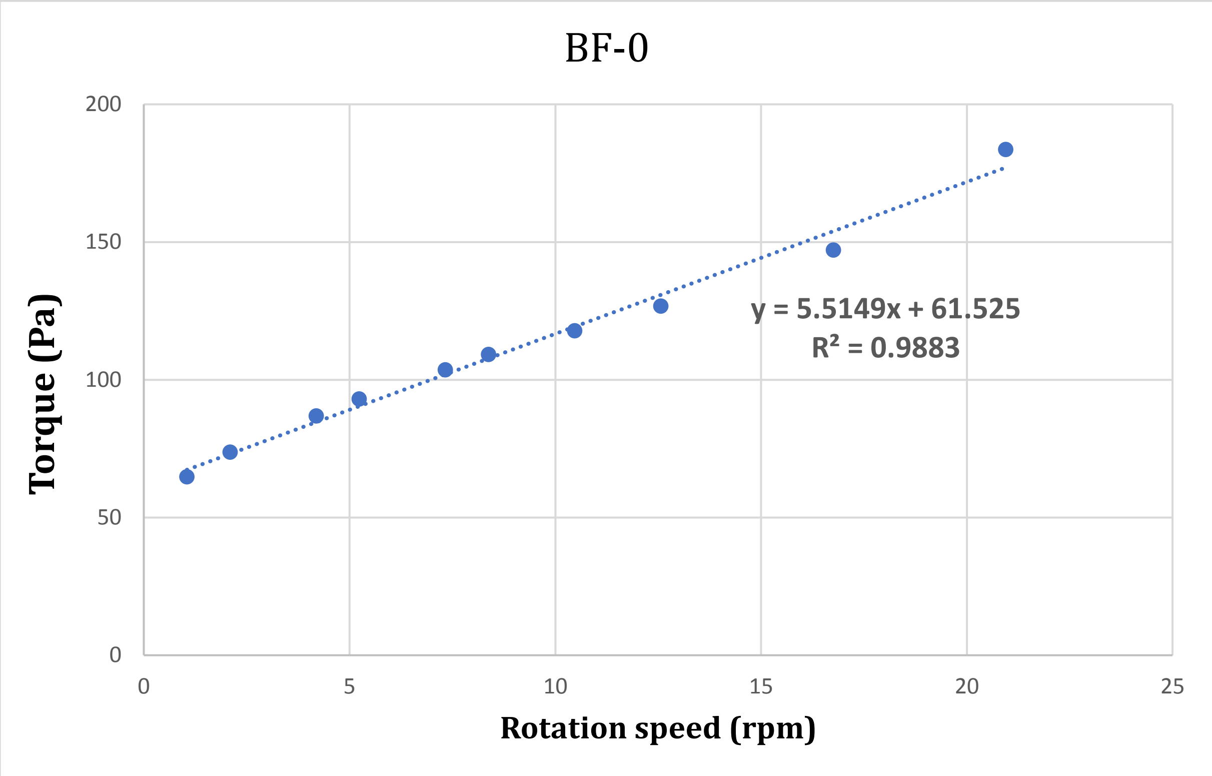
Annex 11: Water absorption results for the wasted bricks

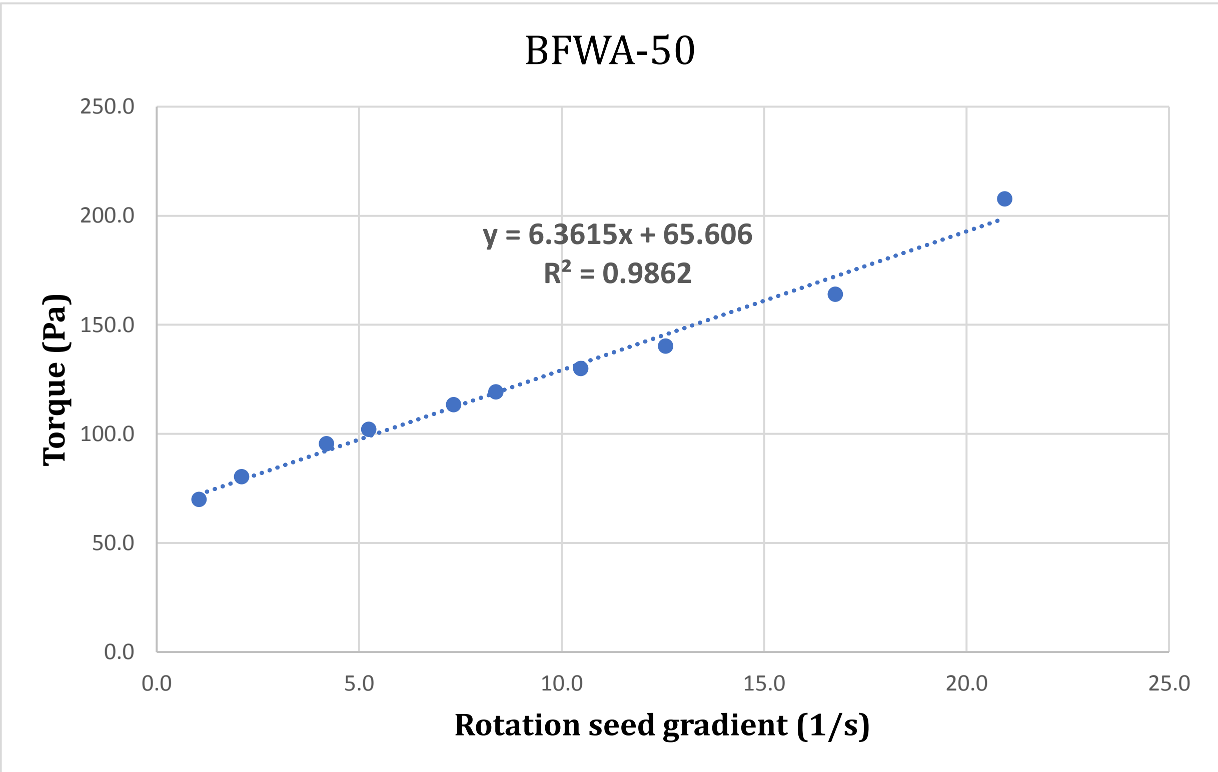
	Coarse pieces of bricks			**Brick sand**			
Parameters	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3	Sample 4
Tare (g)	263.81	70.86	73.5	73.65	73.72	72.9	73.18
Wet weight (g)	1064.12	807.83	881.16	290.52	282.53	333.43	310.02
Dry weight (g)	959.75	723.34	791.09	252.99	246.67	288.84	268.3
Water absorption (%)	10.9%	11.7%	11.4%	14.8%	14.5%	15.4%	15.5%

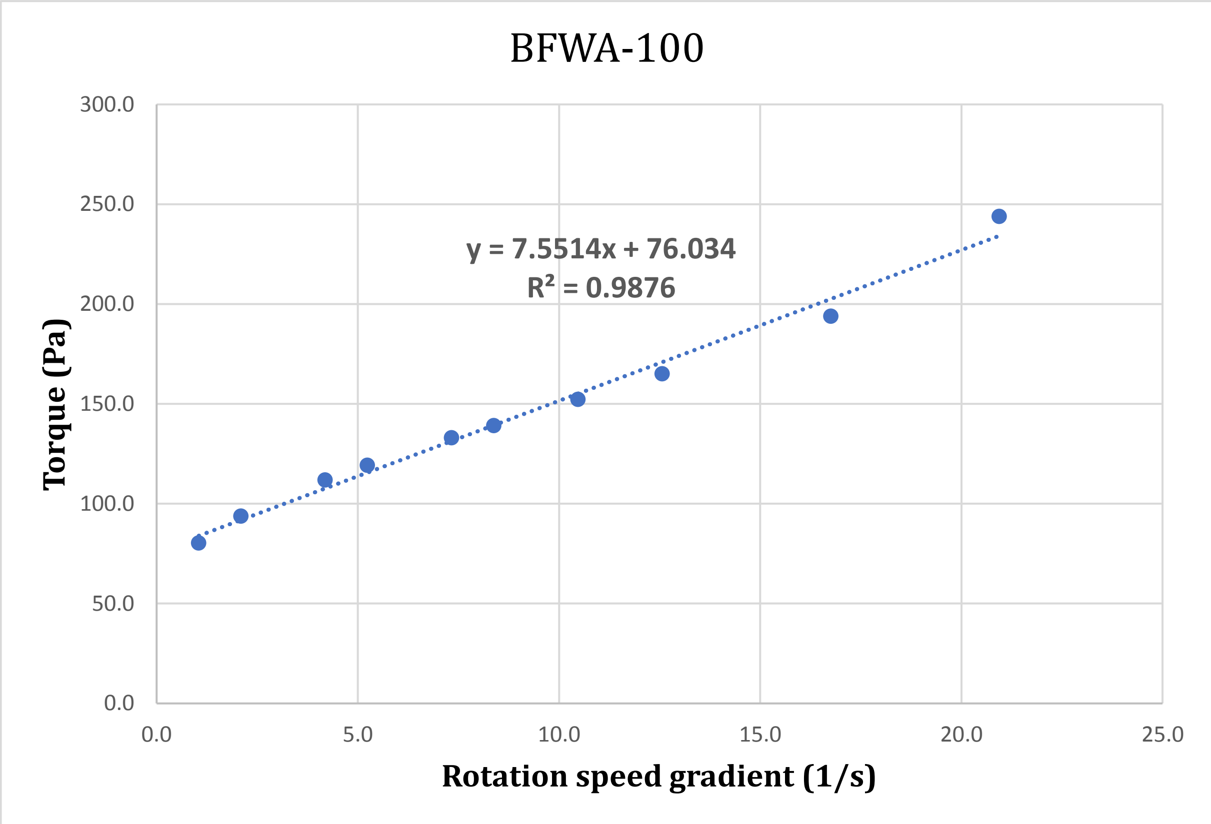
Annex 12: Slump test results for the limestone filler partial substitution with the brick filler

	BF-0		BFWA-50		BFWA-100		BFNWA-50		BFNWA-100	
	Diameter (mm)	Average (mm)	Diameter (mm)	Average (mm)	Diameter (mm)	Average (mm)	Diameter (mm)	Average (mm)	Diameter (mm)	Average (mm)
Mini cone	153	**150.5**	162	**163.25**	148	**146.75**	132	**131.75**	112	**111.75**
	152		164		147		132		113	
	148		167		145		132		112	
	149		160		147		131		110	
MBE cone	194	**193.25**	205	**204.75**	194	**191**	174	**173.5**	144	**143.25**
	189		200		186		176		141	
	193		204		188		170		140	
	197		210		196		174		148	

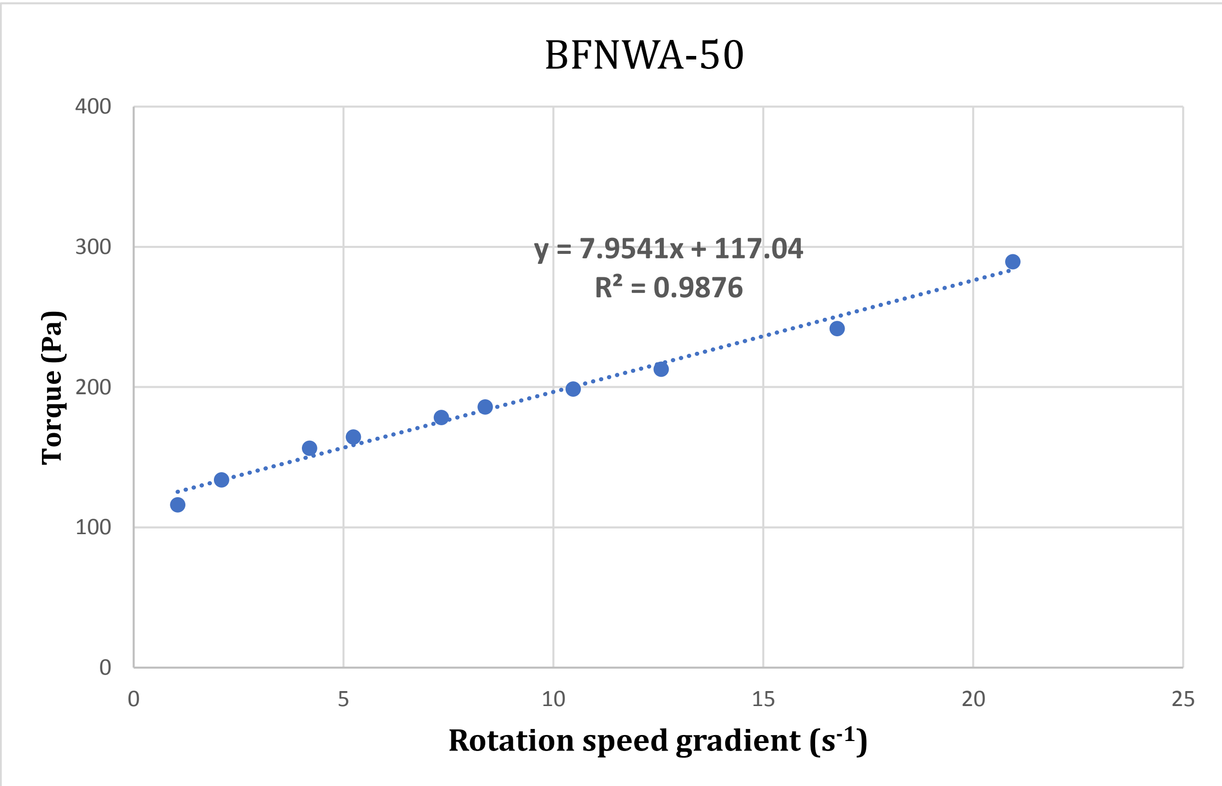
Annex 13: *RheoCAD* results for the limestone filler substitution



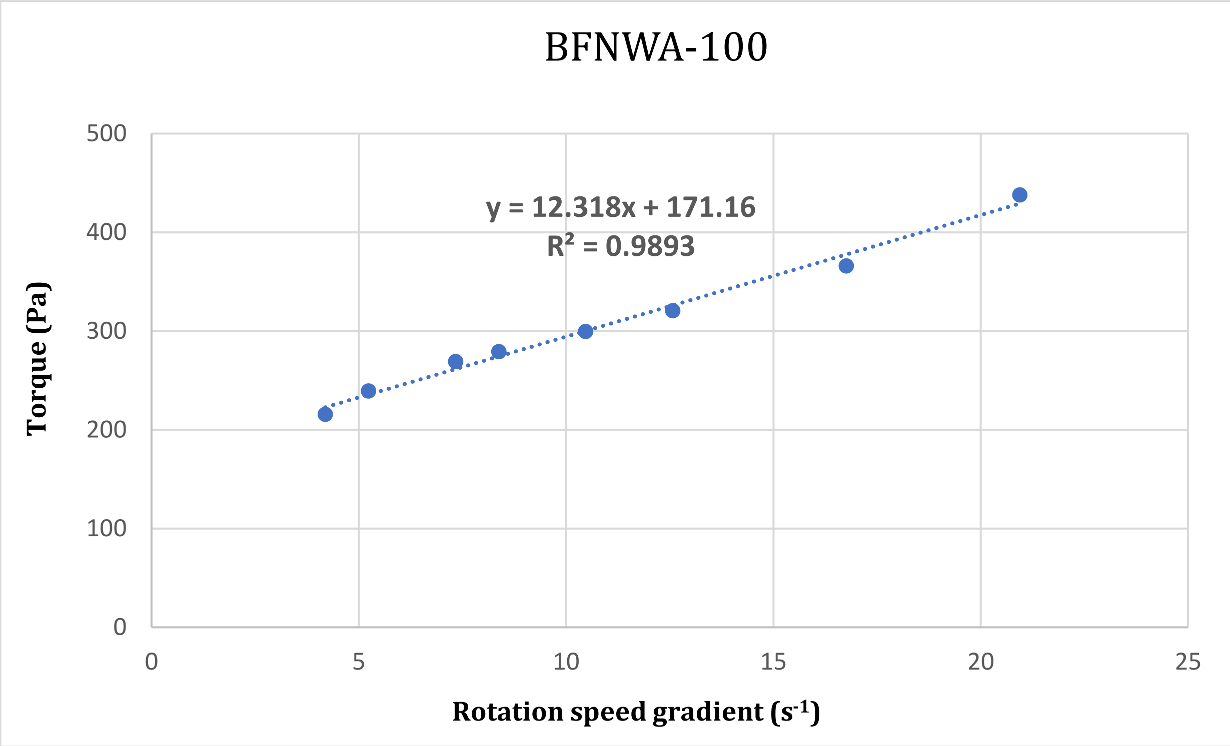




BFWA-100
y = 7.5514x + 76.034
R² = 0.9876
Torque (Pa)
300.0
250.0
200.0
150.0
100.0
50.0
0.0
0.0
5.0
10.0
15.0
20.0
25.0
Rotation speed gradient (1/s)



BFNWA-50
y = 7.9541x + 117.04
R² = 0.9876
Torque (Pa)
400
300
200
100
0
0
5
10
15
20
25
Rotation speed gradient (s-1)

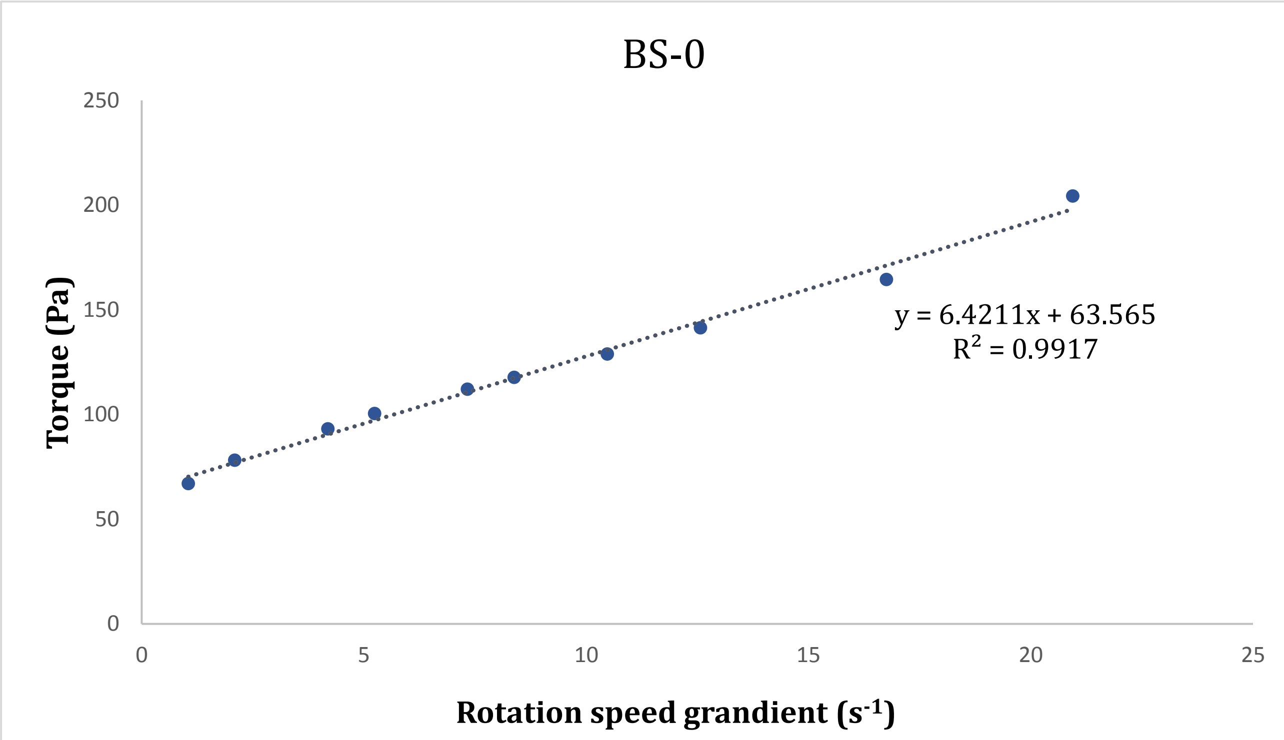


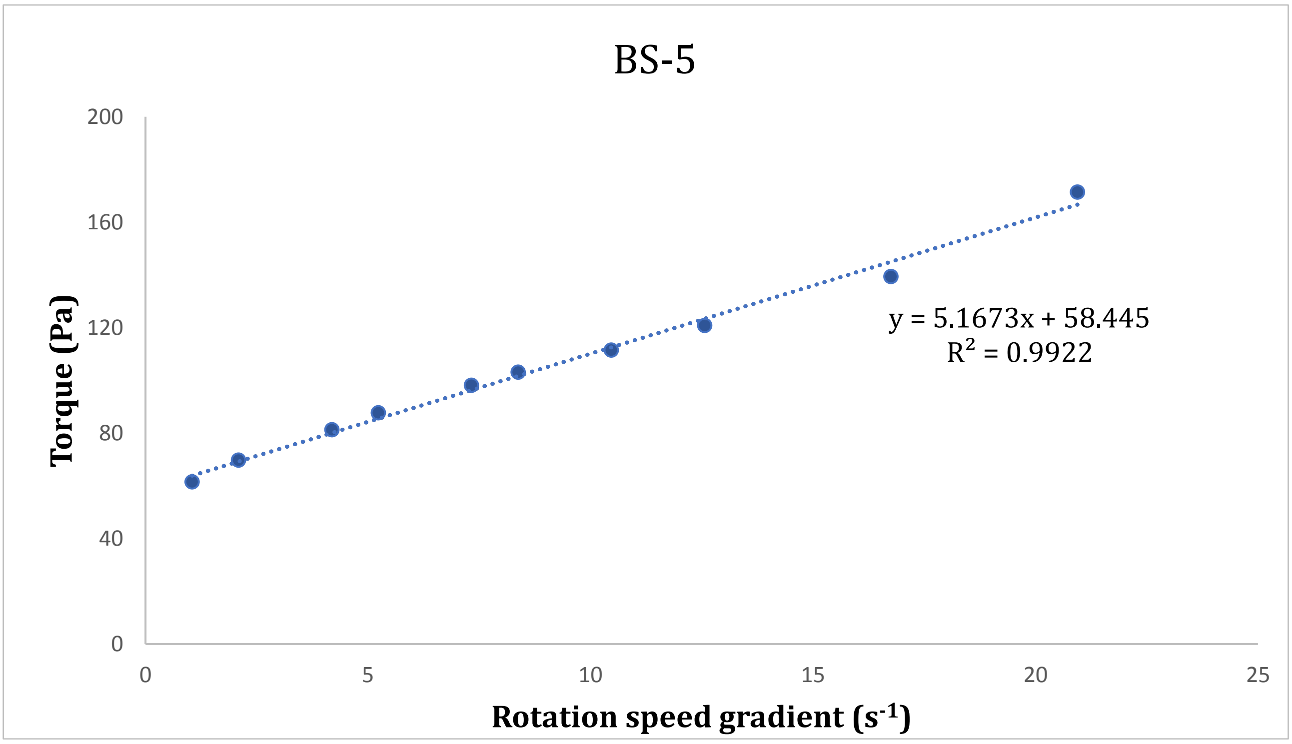
BFNWA-100
y = 12.318x + 171.16
R² = 0.9893
Torque (Pa)
Rotation speed gradient (s-1)
500
400
300
200
100
0
0
5
10
15
20
25

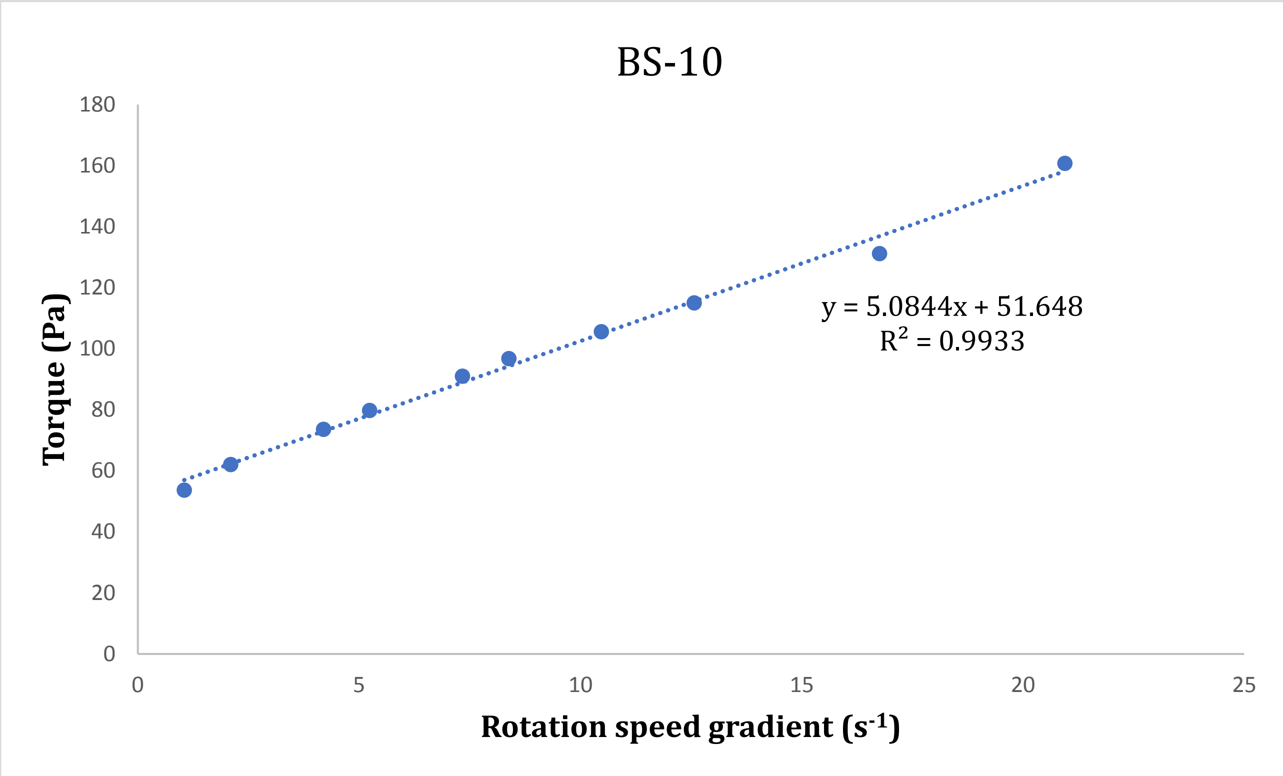
Annex 14: Slump test results for the limestone sand partial substitution by the brick sand

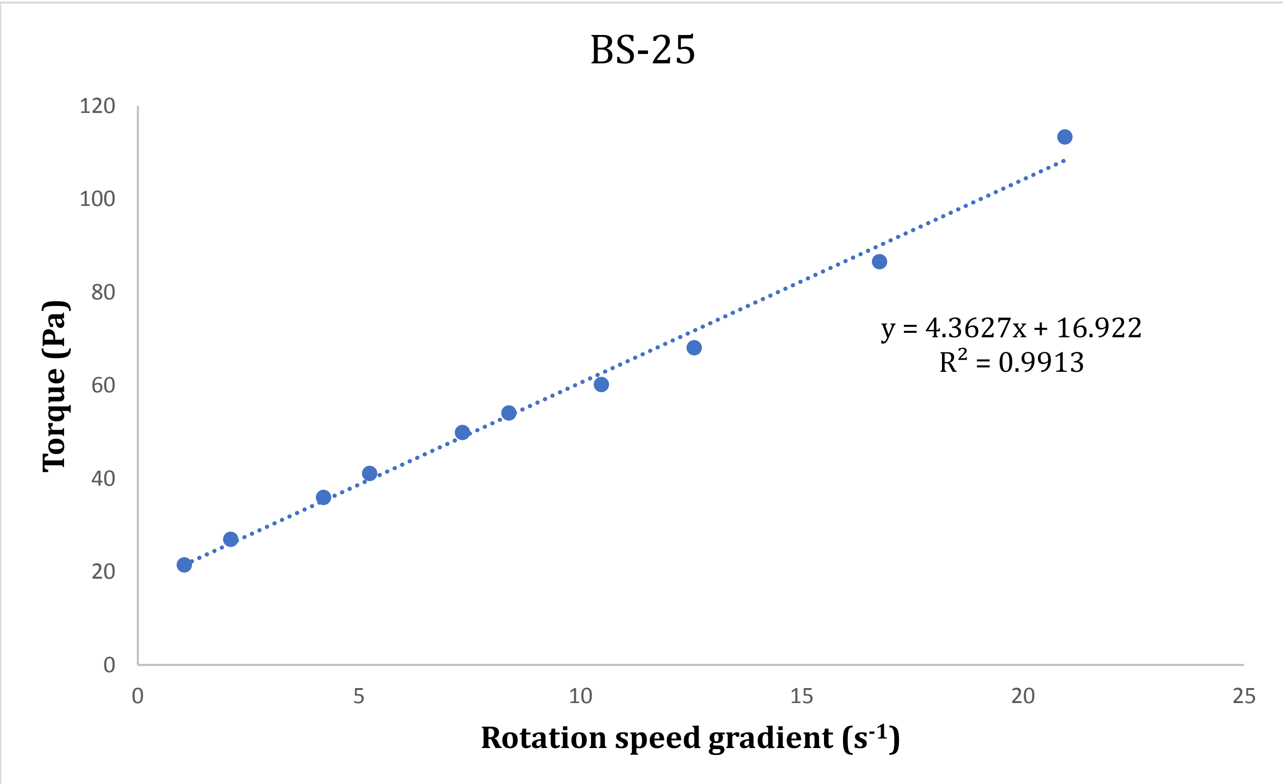
	BS-0		BS-5		BS-10		BS-25		BS-50	
	Diameters (mm)	Average (mm)	Diameters (mm)	Average (mm)	Diameters (mm)	Average (mm)	Diameters (mm)	Average (mm)	Diameters (mm)	Average (mm)
Mini cone	152	**153**	161	163.5	169	**171.25**	154	**155.25**	150	**148.25**
	152		165		170		154		148	
	154		165		172		158		146	
	154		162		174		155		149	
MBE cone	199	**201.75**	218	218	225	**226.25**	220	**217**	200	**203.5**
	204		217		229		218		204	
	205		216		226		215		205	
	199		221		225		215		205	

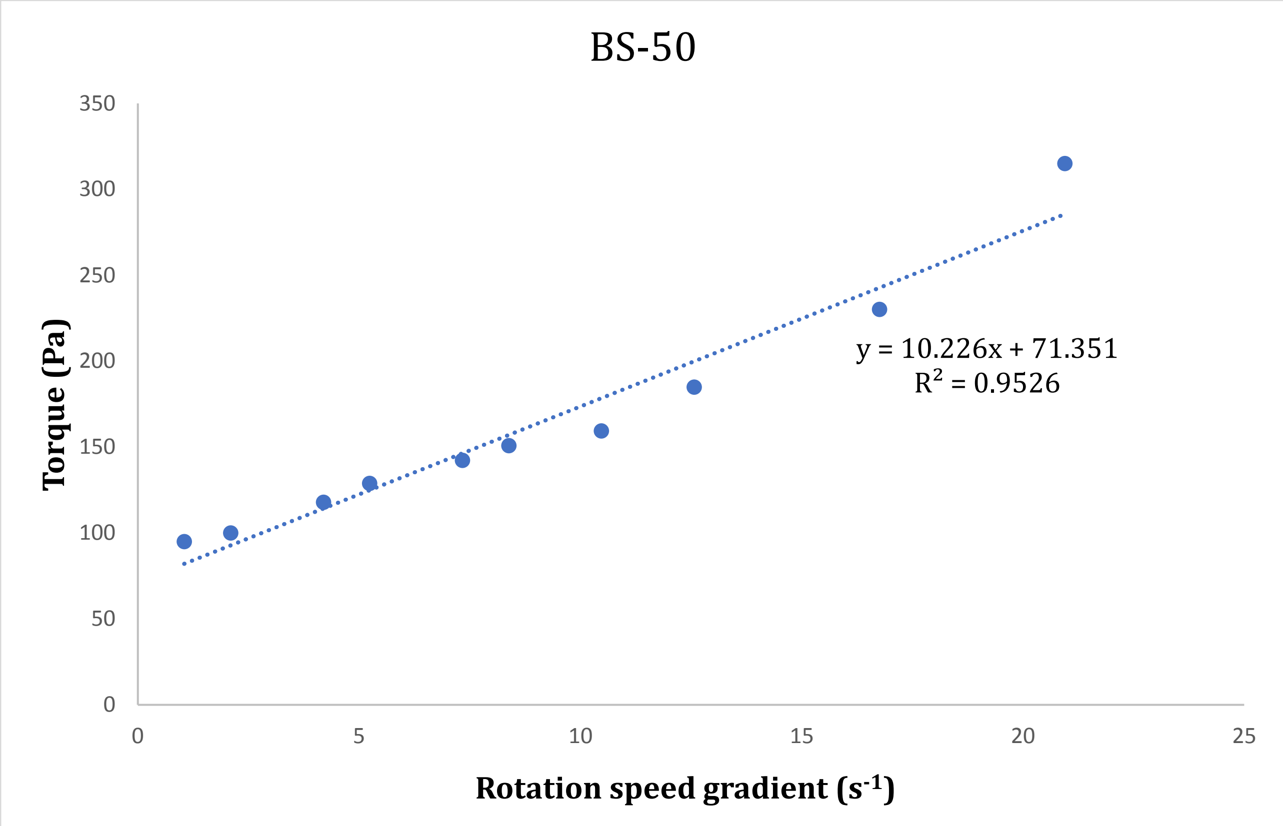
Annex 15: *RheoCAD* results for the limestone sand substitution case






BS-10
180
160
140
120
100
80
60
40
20
0
Torque (Pa)
0
5
10
15
20
25
Rotation speed gradient (s-1)
y = 5.0844x + 51.648
R² = 0.9933


BS-25
120
100
80
60
40
20
0
Torque (Pa)
0
5
10
15
20
25
Rotation speed gradient (s-1)
y = 4.3627x + 16.922
R² = 0.9913



BS-50
350
300
250
200
150
100
50
0
Torque (Pa)
0
5
10
15
20
25
Rotation speed gradient (s-1)
y = 10.226x + 71.351
R² = 0.9526

Annex 16: Mechanical properties of the partial substitution of limestone filler

- Flexural strength at 7 days:

BF-0						
Sample	Width [mm]	Thickness [mm]	Mass [g]	Maximum Load [N]	Maximum Constraint [N/mm²]	Volumetric Mass [kg/m³]
1	40.00	40.00	556.31	3044.7	7.14	2173
2	40.00	40.00	558.63	2835.7	6.65	2182
3	40.00	40.00	554.62	2712.2	6.36	2166
Average	40.00	40.00	556.52	2864.2	6.71	2174
Standard dev.	0.0	0.0	2.0	168.1	0.4	7.9

BFWA-50						
Sample	Width [mm]	Thickness [mm]	Mass [g]	Maximum Load [N]	Maximum Constraint [N/mm²]	Volumetric Mass [kg/m³]
1	40.00	40.00	565.47	2781.7	6.52	2209
2	40	40	565	2582	6	2208
3	40.00	40.00	562.63	2732.4	6.40	2198
Average	40.00	40.00	564.42	2698.6	6.32	2205
Standard dev.	0	0	1.6	104.1	0.2	6.1

BFWA-100						
Sample	Width [mm]	Thickness [mm]	Mass [g]	Maximum Load [N]	Maximum Constraint [N/mm²]	Volumetric Mass [kg/m³]
1	40.00	40.00	553.23	2186.3	5.12	2161
2	40.00	40.00	555.41	2291.5	5.37	2170
3	40.00	40.00	552.76	2240.4	5.25	2159
Average	40.00	40.00	553.80	2239.4	5.25	2163
Standard dev.	0.0	0.0	1.4	52.6	0.1	5.5

BFNWA-50						
Sample	Width [mm]	Thickness [mm]	Mass [g]	Maximum Load [N]	Maximum Constraint [N/mm²]	Volumetric Mass [kg/m³]
1	40.00	40.00	562.39	2236.9	5.24	2197
2	40.00	40.00	562.30	2496.7	5.85	2196
3	40.00	40.00	563.49	2748.4	6.44	2201
Average	40.00	40.00	562.73	2494.0	5.85	2198
Standard dev.	0.0	0.0	0.7	255.8	0.6	2.6

BFNWA-100						
Sample	Width [mm]	Thickness [mm]	Mass [g]	Maximum Load [N]	Maximum Constraint [N/mm²]	Volumetric Mass [kg/m³]
1	40.00	40.00	554.19	2385.4	5.59	2165
2	40.00	40.00	552.68	2438.6	5.72	2159
3	40.00	40.00	554.90	2462.8	5.77	2168
Average	40.00	40.00	553.92	2429.0	5.69	2164
Standard dev.	0.0	0.0	1.1	39.6	0.1	4.4

- Flexural strength at 28 days:

BF-0						
Sample	Width [mm]	Thickness [mm]	Mass [g]	Maximum Load [N]	Maximum Constraint [N/mm²]	Volumetric Mass [kg/m³]
1	40.00	40.00	561.59	3124.5	7.32	2194
2	40.00	40.00	558.52	2977.0	6.98	2182
3	40.00	40.00	561.30	3350.4	7.85	2193
Average	40.00	40.00	560.47	3150.6	7.38	2189
Standard dev.	0.0	0.0	1.7	188.0	0.4	6.6

BFWA-50						
Sample	Width [mm]	Thickness [mm]	Mass [g]	Maximum Load [N]	Maximum Constraint [N/mm²]	Volumetric Mass [kg/m³]
1	40.00	40.00	566.43	3275.7	7.68	2213
2	40.00	40.00	568.16	3171.4	7.43	2219
3	40.00	40.00	564.56	2995.0	7.02	2205
Average	40.00	40.00	566.38	3147.4	7.38	2212
Standard dev.	0.0	0.0	1.8	141.9	0.3	7.0

BFWA-100						
Sample	Width [mm]	Thickness [mm]	Mass [g]	Maximum Load [N]	Maximum Constraint [N/mm²]	Volumetric Mass [kg/m³]
1	40.00	40.00	544.64	3149.4	7.38	2128
2	40.00	40.00	546.13	3130.3	7.34	2133
3	40.00	40.00	550.11	2820.1	6.61	2149
Average	40.00	40.00	546.96	3033.3	7.11	2137
Standard dev.	0.0	0.0	2.8	184.8	0.4	11.0

BFNWA-50						
Sample	Width [mm]	Thickness [mm]	Mass [g]	Maximum Load [N]	Maximum Constraint [N/mm²]	Volumetric Mass [kg/m³]
1	40.00	40.00	561.31	3031.4	7.10	2193
2	40.00	40.00	561.08	2873.7	6.74	2192
3	40.00	40.00	561.42	3029.1	7.10	2193
Average	40.00	40.00	561.27	2978.1	6.98	2192
Standard dev.	0.0	0.0	0.2	90.4	0.2	0.7

BFNWA-100						
Sample	Width [mm]	Thickness [mm]	Mass [g]	Maximum Load [N]	Maximum Constraint [N/mm²]	Volumetric Mass [kg/m³]
1	40.00	40.00	557.34	3366.8	7.89	2177
2	40.00	40.00	553.39	3215.5	7.54	2162
3	40.00	40.00	556.17	3296.5	7.73	2173
Average	40.00	40.00	555.63	3292.9	7.72	2170
Standard dev.	0.0	0.0	2.0	75.7	0.2	7.9

- Compressive strength at 7 days:

BF-0					
Sample	Length [mm]	Width [mm]	Height [mm]	Load max [N]	Maximum Load Constraint [MPa]
1	40.00	40.00	40.00	55478	34.67
2	40.00	40.00	40.00	51392	32.12
3	40.00	40.00	40.00	54422	34.01
4	40.00	40.00	40.00	49191	30.74
5	40.00	40.00	40.00	48268	30.17
6	40.00	40.00	40.00	50152	31.35
Average	40.00	40.00	40.00	51484	32.18
Standard dev.	0.00	0.00	0.00	2896.91	1.81

BFWA-50					
Sample	Length [mm]	Width [mm]	Height [mm]	Load max [N]	Maximum Load Constraint [MPa]
1	40.00	40.00	40.00	49206	30.75
2	40.00	40.00	40.00	51413	32.13
3	40.00	40.00	40.00	50782	31.74
4	40.00	40.00	40.00	51866	32.42
5	40.00	40.00	40.00	46622	29.14
6	40.00	40.00	40.00	50672	31.67
Average	40.00	40.00	40.00	50093	31.31
Standard dev.	0.00	0.00	0.00	1925.03	1.20

BFWA-100					
Sample	Length [mm]	Width [mm]	Height [mm]	Load max [N]	Maximum Load Constraint [MPa]
1	40.00	40.00	40.00	42960	26.85
2	40.00	40.00	40.00	45385	28.37
3	40.00	40.00	40.00	40645	25.40
4	40.00	40.00	40.00	43121	26.95
5	40.00	40.00	40.00	41973	26.23
6	40.00	40.00	40.00	43213	27.01
Average	40.00	40.00	40.00	42883	26.80
Standard dev.	0.00	0.00	0.00	1566.63	0.98

BFNWA-50					
Sample	Length [mm]	Width [mm]	Height [mm]	Load max [N]	Maximum Load Constraint [MPa]
1	40.00	40.00	40.00	47935	29.96
2	40.00	40.00	40.00	48384	30.24
3	40.00	40.00	40.00	49834	31.15
4	40.00	40.00	40.00	48216	30.14
5	40.00	40.00	40.00	45094	28.18
6	40.00	40.00	40.00	52215	32.63
Average	40.00	40.00	40.00	48613	30.38
Standard dev.	0.00	0.00	0.00	2346.05	1.47

BFNWA-100					
Sample	Length [mm]	Width [mm]	Height [mm]	Load max [N]	Maximum Load Constraint [MPa]
1	40.00	40.00	40.00	46652	29.16
2	40.00	40.00	40.00	46007	28.75
3	40.00	40.00	40.00	47181	29.49
4	40.00	40.00	40.00	48160	30.10
5	40.00	40.00	40.00	44337	27.71
6	40.00	40.00	40.00	47737	29.84
Average	40.00	40.00	40.00	46679	29.17
Standard dev.	0.00	0.00	0.00	1378.43	0.86

- Compressive strength at 28 days:

BF-0					
Sample	Length [mm]	Width [mm]	Height [mm]	Load max [N]	Maximum Load Constraint [MPa]
1	40.00	40.00	40.00	58427	36.52
2	40.00	40.00	40.00	61440	38.40
3	40.00	40.00	40.00	59839	37.40
4	40.00	40.00	40.00	58948	36.84
5	40.00	40.00	40.00	60116	37.57
6	40.00	40.00	40.00	62274	38.92
Average	40.00	40.00	40.00	60174	37.61
Standard dev.	0.00	0.00	0.00	1461.86	0.91

BFW-50					
Sample	Length [mm]	Width [mm]	Height [mm]	Load max [N]	Maximum Load Constraint [MPa]
1	40.00	40.00	40.00	59945	37.47
2	40.00	40.00	40.00	56613	35.38
3	40.00	40.00	40.00	59314	37.07
4	40.00	40.00	40.00	58503	36.56
5	40.00	40.00	40.00	55413	34.63
6	40.00	40.00	40.00	59406	37.13
Average	40.00	40.00	40.00	58199	36.37
Standard dev.	0.00	0.00	0.00	1795.30	1.12

BFWA-100					
Sample	Length [mm]	Width [mm]	Height [mm]	Load max [N]	Maximum Load Constraint [MPa]
1	40.00	40.00	40.00	59378	37.11
2	40.00	40.00	40.00	55121	34.45
3	40.00	40.00	40.00	58294	36.43
4	40.00	40.00	40.00	58938	36.84
5	40.00	40.00	40.00	52730	32.96
6	40.00	40.00	40.00	57384	35.86
Average	40.00	40.00	40.00	56974	35.61
Standard dev.	0.00	0.00	0.00	2568.76	1.61

BFNWA-50					
Sample	Length [mm]	Width [mm]	Height [mm]	Load max [N]	Maximum Load Constraint [MPa]
1	40.00	40.00	40.00	59855	37.41
2	40.00	40.00	40.00	60585	37.87
3	40.00	40.00	40.00	61933	38.71
4	40.00	40.00	40.00	59790	37.37
5	40.00	40.00	40.00	60277	37.67
6	40.00	40.00	40.00	60036	37.52
Average	40.00	40.00	40.00	60413	37.76
Standard dev.	0.00	0.00	0.00	800.08	0.50

BFNWA-100					
Sample	Length [mm]	Width [mm]	Height [mm]	Load max [N]	Maximum Load Constraint [MPa]
1	40.00	40.00	40.00	58771	36.73
2	40.00	40.00	40.00	65956	41.22
3	40.00	40.00	40.00	65315	40.82
4	40.00	40.00	40.00	62126	38.83
5	40.00	40.00	40.00	61280	38.30
6	40.00	40.00	40.00	64929	40.58
Average	40.00	40.00	40.00	63063	39.41
Standard dev.	0.00	0.00	0.00	2807.07	1.75

Annex 17: Mechanical properties of the partial substitution of limestone sand

- Flexural strength at 14 days:

BS-0						
Sample	Width [mm]	Thickness [mm]	Mass [g]	Maximum Load [N]	Maximum Constraint [N/mm²]	Volumetric Mass [kg/m³]
1	40.00	40.00	558.97	3295.8	7.72	2183
2	40.00	40.00	557.34	3137.7	7.35	2177
3	40.00	40.00	557.41	3230.1	7.57	2177
Avrage	40.00	40.00	557.91	3221.2	7.55	2179
Standard dev.	0.0	0.0	0.9	79.4	0.2	3.6

BS-25						
Sample	Width [mm]	Thickness [mm]	Mass [g]	Maximum Load [N]	Maximum Constraint [N/mm²]	Volumetric Mass [kg/m³]
1	40.00	40.00	564.17	3257.0	7.63	2204
2	40.00	40.00	571.55	3160.1	7.41	2233
3	40.00	40.00	565.05	2989.0	7.01	2207
Avrage	40.00	40.00	566.92	3135.4	7.35	2215
Standard dev.	0.0	0.0	4.0	135.7	0.3	15.7

BS-50						
Sample	Width [mm]	Thickness [mm]	Mass [g]	Maximum Load [N]	Maximum Constraint [N/mm²]	Volumetric Mass [kg/m³]
1	40.00	40.00	555.37	2831.2	6.64	2169
2	40.00	40.00	550.03	3044.8	7.14	2149
3	40.00	40.00	553.25	2572.9	6.03	2161
Avrage	40.00	40.00	552.88	2816.3	6.60	2160
Standard dev.	0.0	0.0	2.7	236.3	0.6	10.5

- Flexural strength at 28 days:

BS-0						
Sample	Width [mm]	Thickness [mm]	Mass [g]	Maximum Load [N]	Maximum Constraint [N/mm²]	Volumetric Mass [kg/m³]
1	40.00	40.00	554.21	3006.6	7.05	2165
2	40.00	40.00	555.22	3212.8	7.53	2169
3	40.00	40.00	553.86	3064.9	7.18	2164
Average	40.00	40.00	554.43	3094.7	7.25	2166
Standard dev.	0.0	0.0	0.7	106.3	0.2	2.8

BS-25						
Sample	Width [mm]	Thickness [mm]	Mass [g]	Maximum Load [N]	Maximum Constraint [N/mm²]	Volumetric Mass [kg/m³]
1	40.00	40.00	553.07	3198.4	7.50	2160
2	40.00	40.00	555.58	3276.0	7.68	2170
3	40.00	40.00	552.84	3100.2	7.27	2160
Average	40.00	40.00	553.83	3191.5	7.48	2163
Standard dev.	0.0	0.0	1.5	88.1	0.2	5.9

BS-50						
Sample	Width [mm]	Thickness [mm]	Mass [g]	Maximum Load [N]	Maximum Constraint [N/mm²]	Volumetric Mass [kg/m³]
1	40.00	40.00	552.82	3680.3	8.63	2159
2	40.00	40.00	551.21	3296.0	7.73	2153
3	40.00	40.00	554.22	3306.5	7.75	2165
Average	40.00	40.00	552.75	3427.6	8.03	2159
Standard dev.	0.0	0.0	1.5	218.9	0.5	5.9

- Compressive strength at 14 days:

BS-0					
Sample	Length [mm]	Width [mm]	Height [mm]	Load max [N]	Maximum Load Constraint [MPa]
1	40.00	40.00	40.00	51646	32.28
2	40.00	40.00	40.00	54105	33.82
3	40.00	40.00	40.00	46995	29.37
4	40.00	40.00	40.00	50575	31.61
5	40.00	40.00	40.00	54093	33.81
6	40.00	40.00	40.00	51325	32.08
Average	40.00	40.00	40.00	51456	32.16
Standard dev.	0.00	0.00	0.00	2634.52	1.65
BS-25					
Sample	Length [mm]	Width [mm]	Height [mm]	Load max [N]	Maximum Load Constraint [MPa]
1	40.00	40.00	40.00	53683	33.55
2	40.00	40.00	40.00	50888	31.81
3	40.00	40.00	40.00	51688	32.30
4	40.00	40.00	40.00	52609	32.88
5	40.00	40.00	40.00	50699	31.69
6	40.00	40.00	40.00	53515	33.45
Average	40.00	40.00	40.00	52180	32.61
Standard dev.	0.00	0.00	0.00	1290.56	0.81
BS-50					
Sample	Length [mm]	Width [mm]	Height [mm]	Load max [N]	Maximum Load Constraint [MPa]
1	40.00	40.00	40.00	58252	36.41
2	40.00	40.00	40.00	59141	36.96
3	40.00	40.00	40.00	56577	35.36
4	40.00	40.00	40.00	59432	37.14
5	40.00	40.00	40.00	49857	31.16
6	40.00	40.00	40.00	61818	38.64
Average	40.00	40.00	40.00	57513	35.95
Standard dev.	0.00	0.00	0.00	4120.68	2.58

- Compressive strength at 28 days:

BS-0					
Sample	Length [mm]	Width [mm]	Height [mm]	Load max [N]	Maximum Load Constraint [MPa]
1	40.00	40.00	40.00	51958	32.47
2	40.00	40.00	40.00	52845	33.03
3	40.00	40.00	40.00	54660	34.16
4	40.00	40.00	40.00	52063	32.54
5	40.00	40.00	40.00	50459	31.54
6	40.00	40.00	40.00	52460	32.79
Average	40.00	40.00	40.00	52408	32.75
Standard dev.	0.00	0.00	0.00	1370.02	0.86

BS-25					
Sample	Length [mm]	Width [mm]	Height [mm]	Load max [N]	Maximum Load Constraint [MPa]
1	40.00	40.00	40.00	50571	31.61
2	40.00	40.00	40.00	51312	32.07
3	40.00	40.00	40.00	52538	32.84
4	40.00	40.00	40.00	51777	32.36
5	40.00	40.00	40.00	49875	31.17
6	40.00	40.00	40.00	48175	30.11
Average	40.00	40.00	40.00	50708	31.69
Standard dev.	0.00	0.00	0.00	1548.11	0.97

BS-50					
Sample	Length [mm]	Width [mm]	Height [mm]	Load max [N]	Maximum Load Constraint [MPa]
1	40.00	40.00	40.00	62780	39.24
2	40.00	40.00	40.00	65340	40.84
3	40.00	40.00	40.00	64347	40.22
4	40.00	40.00	40.00	66724	41.70
5	40.00	40.00	40.00	67132	41.96
6	40.00	40.00	40.00	67141	41.96
Average	40.00	40.00	40.00	65577	40.99
Standard dev.	0.00	0.00	0.00	1764.86	1.10

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