Research Article

Reuse of waste bricks: a new generation of geopolymer bricks

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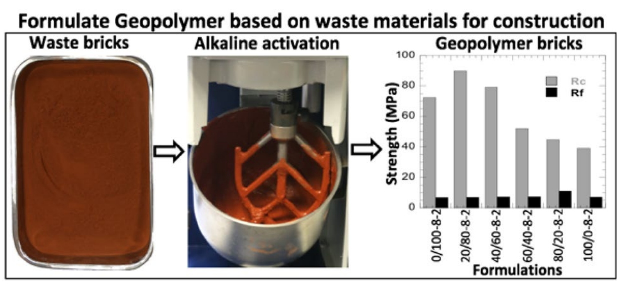
Abstract

In this study, the potential for reuse of waste brick (WB) by alkaline activation in a new geopolymer brick was examined. The effect of the incorporation of ground granulate blast furnace slag (GGBFS), the molarity of sodium hydroxide (NaOH) and the silicate to sodium hydroxide ratio (Na_2SiO_3/NaOH) on the mechanical properties of the final product was investigated. The manufacturing of geopolymer bricks was carried out by mixing WBs, GGBFS, sand with a solution of hydroxide and sodium silicate. The samples were prepared according to different formulations. The optimal compressive strength obtained is 89.91 MPa, for a GGBFS/WB ratio of 80/20, an 8 M molarity of NaOH and a silicate/hydroxide ratio of 2/1. This study shows an effective feasibility for the recovery and recycling of industrial waste into a valuable product for the construction sector. This recycling method can bring environmental and economic benefits by using it as an alternative material to fired brick in construction. Given the results obtained, it will be interesting to study the environmental and economic impact as well as the durability properties of these geopolymer bricks.

Graphical abstract



Keywords Geopolymer · Recovery of waste bricks · GGBFS · Reuse · Alkaline activation · Compressive strength

1 Introduction

The brick is one of the most widely used masonry units for building construction [1]. Common building materials, such as bricks and cement, are responsible for a number of sensitive issues linked to the social and environmental impacts [2]. Conventional bricks are made from raw materials, clay, sand, plastic [high-density polyethylene (HDPE) and polyethylene (PE)] and non-plastic materials, then fired in a kiln at a temperature ranging from 850 to 950 °C [3, 4]. The use of fossil fuels induces large energy consumptions that are responsible

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for economic, energy, environmental and ecological issues [2]. As an example, the production of one tonne of cement requires the consumption of 1.7 tons of raw materials [2] and involves the emission of 0.8 tons of CO_2 into the atmosphere [5]. However, during the industrial production phase, a significant percentage of waste such as fly ash (FA), waste bricks (WB), ground granulated blast furnace slag (GGBFS) is obtained [6]. These wastes result in environmental challenges. The process of recycling and recovering a large amount of waste bricks has become necessary to ensure environmental protection [7].

In 2012, information gathered from 40 countries from six continents around the world showed a critical value of overall construction and demolition waste production that reached more than 3.0 billion tonnes [8] adding an annual production of 500 billion tonnes of blast furnace slag [9] with an increasing trend due to country development.

In France, a huge quantity of fired bricks is produced each year and used in construction activities. The amount of waste brick represents about 3–7% by weight of total production, suggesting that millions of tonnes of waste bricks are produced and disposed of each year in huge landfill areas at brickworks. In the case of the Briqueterie du Nord (BdN), all the waste of bricks or material before firing is directly reused in production line. Waste after firing does not exceed 5% of weight production.

Depending on the characteristics of the waste, including its colour (red or other), it is sold to a clay manufacturing and distribution company (specific to the Templeuve plant in North of France). The portion of this non-red waste is either resold for construction sites in need of hard backfill or used at the quarry to stabilize the runways during winter and wet periods.

The Reuse of this industrial waste by recycling it into new building materials is considered a practical solution for reducing many environmental problems related to pollution. However, this waste can only be recycled if its environmental properties and behaviors complies with specific requirements and respond to a relevant environmental standards [10].

Many studies have been done to incorporate fired clay waste bricks into the production process of different building materials, one of these technique is the geopolymerization [11–14].

Geopolymerization is one of the best techniques of recycling waste in the production of a new construction material that meets both standards and practice-oriented applications [15].

Geopolymerization is the processing technique used to produce new geopolymer-based materials. Geopolymers are alkaline aluminosilicate binders, which can be a substitute for building materials [15].

The term Geopolymer is used to characterize a classification of alumino-silicate materials manufactured mainly for the substitution purpose of ordinary portland cement (OPC) in concrete [16]. The term was first introduced by Joseph Davidovits in the 1970s, although comparable materials were created in the previous Soviet Union since the 1950s, but were called soil cements [17].

The geopolymers are generally made of pozzolanic materials such as kaolin, metakaolin, GGBFS, fly ash and ceramic waste [18, 19]. These materials are activated by an alkaline solution generally containing varying amounts of dissolved silicium [20]. They have a wide range of applications thanks to their properties such as resistance to acid attack, fire and high temperatures [21].

The main characteristic of geopolymers is their ability to provide an important reduction in CO_2 emissions and less energy requirements for production compared with Ordinary Portland Cement products thanks to the low curing temperature used [20]. Geopolymers can be considered a green concrete [22].

Many work throught the literature, presented different technique of optimizing different aspect of the geopolymer formulation, from material composition to uses of recycled waste. Reig et al. [23] have shown that optimizing the type and concentration of the alkaline activator can produce mortar samples with a compressive strength up to 50 MPa after 7 days of curing at 65 °C. Letelier et al. [24] studied the mechanical properties of concrete prepared with a combination of recycled aggregates and waste bricks. The combination of fly ash and waste bricks was presented by Rovanîk et al. [25]. Another study on the recycling of waste bricks and slag into new building material was presented by Zawrah et al. [26].

GGBFS is a waste produced by the iron blast furnace and subsequently tempered, and it is essentially composed by calcium alumino-silicate which is overload [26]. The GGBFS can be added to the geopolymer formulation since this component was proven to be one of the best activated materials, resulting in an increase in compressive strength and other mechanical properties [27, 28]. The alkaline activation required for the geopolymerization process is generally provided by the addition of solutions such as sodium hydroxide and sodium silicate [29]. Theses study oriented the research on focusing on finding optimal ratio incorporated in the formulation of this geopolymer. Four properties were investigated by order of priority, compressive strength, incorporation of GGBFS, dissolution of hydroxide and the activator to hydroxide ratio.

The main objective of this research is to develop a new geopolymer for the building construction sector by using waste bricks as a solid precursor. In addition to waste bricks, other minerals are used for alkaline activation such as blast furnace slag and sand. Three properties were considered: the ratio of GGBFS/WB, the molarity of sodium hydroxide and the silicate to hydroxide ratio. The optimal value of each parameter was determined in this study. It should be noted that the preparation of geopolymer binder is not thermally activated. Thermal activation increases reactivity but also induces cost value, thus increases the economic cost of the material. Hence the importance of this work is to develop a new material at room temperature that can be a substitute for fired bricks. The scope of this research also includes the strength behavior for the mixtures of blast furnace slag and waste bricks alkali activated.

2 Materials and methods

2.1 Materials

The materials used in this experimental study are waste bricks (WB), sodium hydroxide (NaOH), sodium silicate (Na_2SiO_3), sand and ground granulated blast furnace slag (GGBFS).

The waste bricks and sand used in this work was supplied by the company BdN (Briqueterie du Nord) located in Lille (North of France). The waste bricks is crushed and sieved with the sand using a 400 µm sieve.

The sand used in this preparation of geopolymer bricks was the same as the one used for the fired brick preparation of BDN. The choice was made to keep a uniform matrix as fired bricks made of clay and sand. The GGBFS was used based on composition and it is essentially composed of a balanced aluminosilicate matrix with a calcium overload. It is well known for incorporation into geopolymer systems to increase compressive strength and improve the development of resistance at room temperature [30]. The alkaline activator used in the preparation of geopolymer bricks is a combination of hydroxide and sodium silicate. This choices is intended to have a positive effect due to the small ionic size of Na^+ which makes it more active and promotes a better dissolution of the raw material [31]. Reactions occur at a high rate when the alkaline activator contains soluble silicate compared to using only a hydroxide solution [32]. Hence the combination of silicate and sodium hydroxide was used in the preparation of geopolymer bricks (Table 1).

Table 1 All abbreviated words used throughout the manuscript

Word	Abbreviation
High density polyethylene	HDPE
Polyetylene	PE
Fly ash	FA
Waste brick	WB
Ground granulated blast furnace slag	GGBFS
Briqueterie du nord	BdN
Ordinary portland cement	OPC
Sodium hydroxide	NaOH
Sodium silicate	Na_2SiO_3

2.2 Chemical composition of solid materials

The chemical composition of waste bricks, blast furnace slag and sand, was obtained using the S4 BRUCKER X-ray fluorescence dispersion spectrometry technique. Table 2 presents the chemical composition of WB, GGBFS, and sand used in the preparation of geopolymer brick.

Table 2 Chemical composition of waste bricks (WB), slag (GGBFS) and sand

Chemical composition (wt%)	WB	GGBFS	Sand
MgO	1.41	5.76	0.47
Al_2O_3	12.68	9.16	5.57
SiO_2	73.106	33.84	89.99
K_2O	3.45	0.54	1.2
CaO	1.02	49.17	0.19
TiO_2	0.87	0.77	0.2
MnO	0.68	0.3	0.02
Fe_2O_3	6.74	0.46	2.35
Ni_2O_3	0.009	–	0.01
Cu_2O	0.007	–	–
ZnO	0.02	–	–
GaO_3	0.008	–	–

The chemical composition of waste bricks indicates that the SiO_2 content is 76.106% by mass against 12.68% by mass for Al_2O_3. The SiO_2/Al_2O_3 molar ratio is 6, which classify the waste bricks as siliceous material [33]. The GGBFS is composed by two majors parts: 33.84% SiO_2 and 49.17% CaO by mass, with a minority of 9.16% Al_2O_3. SiO_2 represents the major phase of sand with 89.99% of its chemical composition.

2.3 Mineralogical characterization of solid materials

The mineralogical composition was determined by X-ray diffraction analysis (XRD), using a D8 Advance BRUCKER AXS energy dispersive diffractometer as apparatus. This last composition makes possible the identification of different crystallized mineral phases in the sample.

Data in Fig. 1 show that quartz (SiO_2) is the main crystalline phase in the waste bricks. Calcite (CaCO3) and

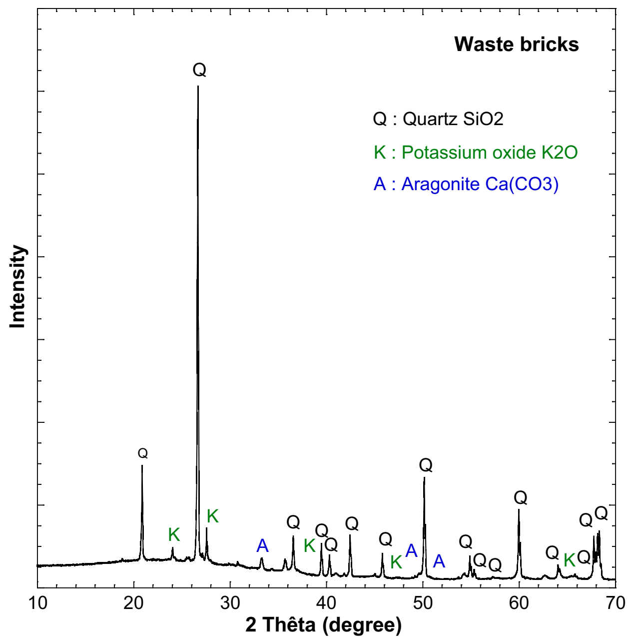

Fig. 1 XRD of waste bricks

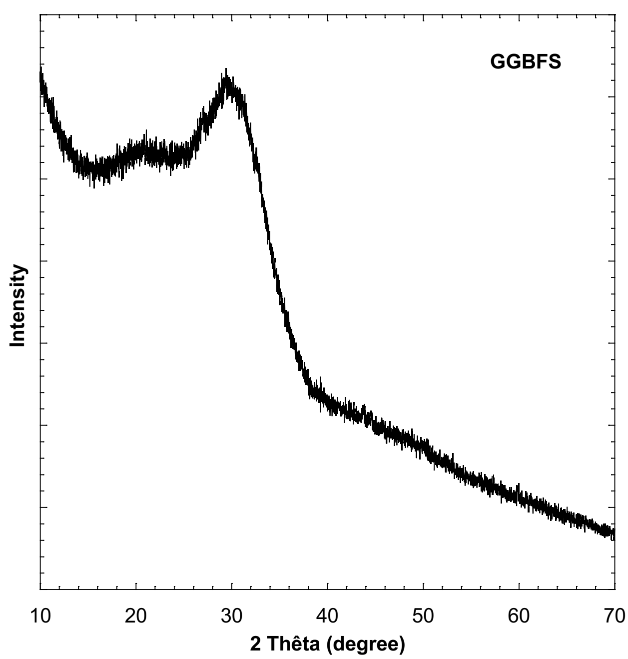

Fig. 2 XRD of GGBFS

potassium oxide (K_2O) were also identified as minor constituents [23, 34].

Figure 2 illustrates the mineralogical composition of the GGBFS. Quartz (SiO_2) and calcium oxide (CaO) are the main phases [35]. The amorphous hump displayed in the XRD analysis of the GGBFS indicates that a large amount of glass is present [36].

2.4 Alkaline activators

The combination of silicate and sodium hydroxide was used as an alkaline activator for the preparation of geopolymer bricks. Sodium silicate is composed of 27% SiO_2, 8% Na_2O, and 65% H_2O (by mass) [37, 38]. NaOH with a purity of 98% was supplied in solid capsules forms [39, 40]. Sodium hydroxide is prepared in different concentrations of 6 M, 8 M, 10 M, 12 M and 14 M. The two solutions of NaOH and Na_2SiO_3 were mixed 24 h before the geopolymer bricks samples were prepared to obtain the homogeneity of the total solution.

3 Experimental methods

Geopolymer bricks were prepared by mixing the solid precursors: 50% sand and 50% (WB and GGBFS) with an alkaline solution of silicate and sodium hydroxide. All the formulations prepared in our study contain 50% of sand by weight. The variation is reflected only in the percentages of WB and GGBFS. Various studies have shown that the order of preparation and the method of mixing materials have a very important role to play in achieving good results [21].

To obtain a homogeneous geopolymer binder, dry solid materials were mixed for 3 min, then the alkaline solution were added, and the mixing remained for 6 min in order to get an homogenous binder. The liquid/solid ratio used is 0.4 by weight, using a mixer with a capacity of 5 l.

After mixing, five prismatic samples of $40 \times 40 \times 160$ mm^3 were molded for each formulation to measure flexural and compressive strengths. These numbers of samples were used to ensure the reproducibility of the strength testings. Hence, the means of the prepared samples are calculated.

In this study, geopolymer bricks are formulated according to the following three properties:

- The GGBFS to WB ratio;
- The molarity of NaOH;
- The silicate to hydroxide (S/H) ratio of the alkaline solution.

3.1 Preparation of samples with different GGBFS/WB ratio

The type of additives has a central influence on geopolymerization [41]. Several studies have shown that calcium accelerates the reaction of geopolymerization and increases the compressive strength of geopolymers [28, 42]. This increase is caused by the reaction of calcium compounds with the geopolymer binder. The results show that the inclusion of these additives in the binary mixed binder is effective in improving the mechanical performance of geopolymers based on waste bricks [43]. To optimize the GGBFS/WB ratio in the geopolymer formulation, the variation in compressive and flexural strengths, as a function of the GGBFS/WB ratio, was studied. The 40x40x160 mm^3 prismatic samples are prepared according to different GGBFS/WB ratios, while the NaOH molarity and Na_2SiO_3/NaOH mass ratio have been set at 10 M and 2.5 respectively as highlighted in Table 2.

3.2 Preparation of samples with different molarity of NaOH

The presence of a sufficient quantity of NaOH in the liquid phase have an essential role in the geopolymerization reaction [44]. NaOH reacts as a dissolving agent for aluminum and silicium [45]. Based on the literature, the range of molarity from 6 to 14 M are used to optimize the maximum dissolution of the aluminosilicate material. To evaluate the effect of NaOH molarity on the compressive and flexural strengths, a series of 40 × 40 × 160 mm^3 samples of geopolymer bricks were prepared with a Na_2SiO_3/NaOH mass ratio of 2.5, a GGBFS/WB mass ratio = 80/20, and with different molarities of NaOH as illustrated in the Table 2.

3.3 Preparation of samples with variable silicate-to-hydroxide ratio (S/H)

The combination of sodium (or potassium silicate) and sodium hydroxide (or potassium hydroxide) is the most common alkaline liquid combination used for geopolymerization reactions [46]. Studies have shown that kinetics of these reactions and properties of geopolymers are affected by the SiO_2/Al_2O_3 ratio and the Na–Si–Al bond formed [47]. Excess of NaOH in the mixture causes microcracks in the prepared geopolymer samples, and small amounts of NaOH is insufficient for silica leaching and alumina oxides in the geopolymerization reaction [48]. Therefore, to obtain the best geopolymerization results, it is necessary to optimize the silicate to hydroxide ratio used in the geopolymerization reaction. A final series of prismatic geopolymer bricks samples were prepared to optimize the silicate/hydroxide (S/H) ratio. These samples are prepared according to four formulations so that the GGBFS/WB ratio and NaOH molarity are fixed while the S/H ratio is variable.

The GGBFS/WB ratio used was the optimum resulting from the first tests (GGBFS/WB = 80/20), with the optimal molarity obtained for NaOH (NaOH 8 M).

Table 3 presents the different samples prepared with the percentages of GGBFS, WB, the NaOH molarity and the S/H ratio.

All prepared samples are named as follow GWB x/y–m–r, with:

- x/y is the mass ratio GGBFS/WB, which ranges from 0/100 to 100/0.
- m is the molarity of NaOH, with m = 6, 8, 10, 12 or 14.
- r is the silicate/hydroxide mass ratio, with r = 1.5, 2, 2.5 or 3.

3.4 Sample's hardening properties and strength testing

The hardening of samples is carried out according to a well-defined experimental protocol presented in Fig. 3. The steps are as follow:

- 40 × 40 × 160 mm^3 samples are demolded after 30 min;
- During the first 4 days of curing, samples are left at room temperature (around 23 °C) and a relative humidity of 80%, by using a saturated aqueous solution [49];
- Samples are put in the oven at 40 °C for 12 days at a relative humidity of 80% [49];
- Then, the temperature of curing is increased to 110 °C for 12 h.

Table 3 Properties of all prepared samples

Samples	GGBFS (%)	WB (%)	NaOH molarity (M)	S/H
Optimization of the GGBFS/WB ratio				
GWB 100/0-10-2.5	100	0	10	2.5
GWB 80/20-10-2.5	80	20	10	2.5
GWB 60/40-10-2.5	60	40	10	2.5
GWB 40/60-10-2.5	40	60	10	2.5
GWB 20/80-10-2.5	20	80	10	2.5
GWB 0/100-10-2.5	0	100	10	2.5
Optimization of NaOH molarity				
GWB 80/20-6-2.5	80	20	6	2.5
GWB 80/20-8-2.5	80	20	8	2.5
GWB 80/20-10-2.5	80	20	10	2.5
GWB 80/20-12-2.5	80	20	12	2.5
GWB 80/20-14-2.5	80	20	14	2.5
Optimization of the silicate-to-hydroxide ratio (S/H)				
GWB 80/20-8-1.5	80	20	8	1.5
GWB 80/20-8-2	80	20	8	2
GWB 80/20-8-2.5	80	20	8	2.5
GWB 80/20-8-3	80	20	8	3

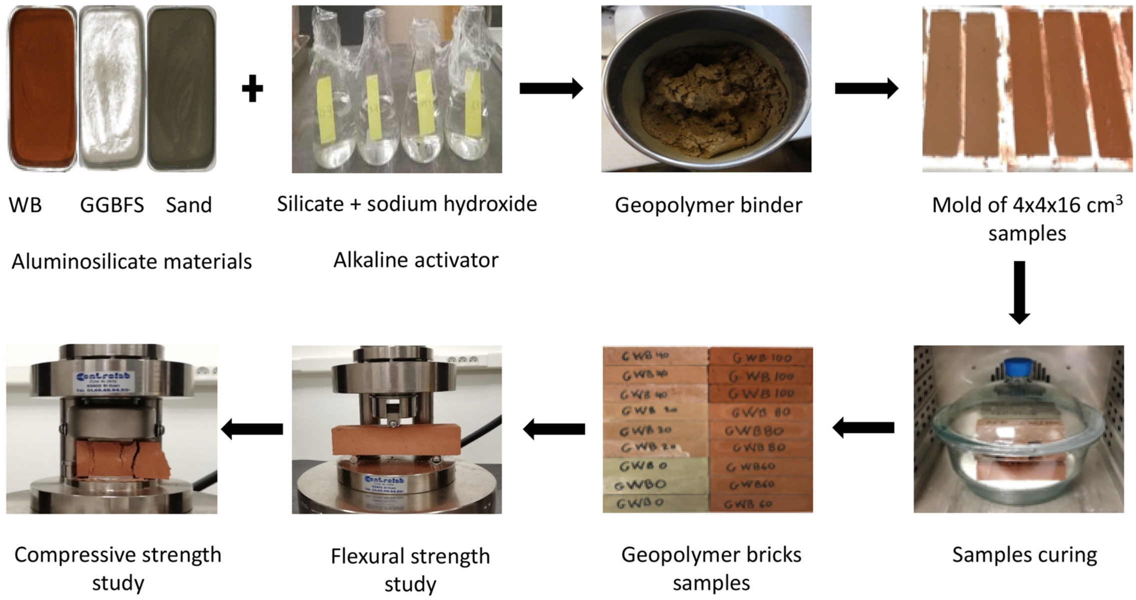

Fig. 3 Methodology of sample preparation, curing and strength testing

Finally, the flexural and compressive strengths are determined for these samples and the hardened properties of each sample type was measured as illustrated in the Fig. 3. The values shown in this study represent an average obtained from five geopolymer bricks samples. All these resistances have been evaluated according to NF P15-471-1 (for flexural) and NF EN 196-1 (for compression). For the flexural strength tests on prismatic samples, a multi-purpose test machine with a loading speed of 3 kN/min was used. For compressive strength measurements on cubic samples, the same machine was used with a loading speed of 144 kN/min.

4 Results and discussion

4.1 GGBFS/WB ratio

Figure 4 shows the variation of compressive and flexural strengths with GGBFS/WB ratio. The GGBFS/WB ratio = 0/100, has a compressive strength of 38.51 MPa which is higher than a traditional fired bricks [45].

However, compressive strength evolves with the increase in the percentage of GGBFS in the formulation of the geopolymer bricks studied. For a ratio GGBFS/WB = 20/80, the compressive strength is 39.65 MPa. This resistance increases to 57.96 MPa for the ratio of GGBFS/WB = 80/20. Beyond this ratio, this resistance decreases to 50.58 MPa, for a GGBFS/WB = 100/0 ratio. Therefore, the optimal ratio between blast furnace slag and waste bricks is GGBFS/WB = 80/20.

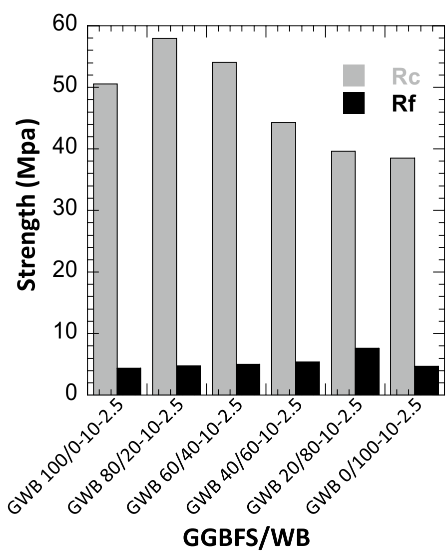

Fig. 4 Variation in compressive and flexural strength samples prepared with different GGBFS/WB ratios

The GGBFS/WB = 20/80 ratio gives the highest flexural strength value is 7.6 MPa. Other flexural resistances are lower because of the presence of blast furnace slag, which results in rapid setting and leads to the formation of microcracks. When microcracks are identified, the propagation of the main crack caused by flexural is rapid. It can be noted that, with the increase in dosage of blast furnace slag, the flexural resistance decreases. The optimal flexural strength ratio of blast furnace slag and waste bricks is GGBFS/WB = 20/80.

The improvement in compressive strength is mainly due to the inclusion of blast furnace slag in the matrix, which leads to the reinforcement of the geopolymer binder. In addition, the amount of calcium oxide (CaO) contained in the ground granulated blast furnace slag precursor (GGBFS) was found to have a significant impact on the resulting cured geopolymer and therefore shows an improvement in the mechanical properties of the specimens [26].

4.2 Effect of NaOH molarity

Figure 5 highlights the effect of the molarity of NaOH (6 M, 8 M, 10 M, 12 M and 14 M) on the compressive and flexural strengths. The optimal compressive strength was obtained using 8 M NaOH, with a value of 78.4 MPa. The lowest resistance was noticed at 47.61 MPa for a molarity of 14 M. Formulations with 6 M, 10 M and 12 M molarities have a moderate resistance, respectively 59.39 MPa, 57.96 MPa, and 51.69 MPa.

The optimal resistance is obtained using 8 M NaOH, with a value of 6.21 MPa. For 6 M and 10 M, we had respectively a flexural strength of 6.01 MPa and 4.77 MPa. For both formulations with 12 M and 14 M molarities, the results reveal approximately the same resistances, respectively 3.13 MPa and 3.12 MPa. Therefore, NaOH 8 M is considered the optimal concentration for a maximum compressive and flexural strength.

These results are consistent with those of other researchers [50]. The molarity of NaOH has a significant effect as an activating solution on the mechanical strength of geopolymer samples. In the geopolymer reaction, the increase in molarity will favour an acceleration of the reaction rate due to the increase in soluble silicate and the higher concentration of reagents [47]. The effect of NaOH on geopolymerization is explained by the greater dissolution of aluminosilicate minerals in the NaOH solution, thus a greater number of oligomers are formed and develop a higher compressive strength.

4.3 Silicate/hydroxide ratio

The evolution of compressive and flexural strengths with the Na_2SiO_3/NaOH ratio is provided by Fig. 6. Na_2SiO_3/NaOH = 2 ratio gives the maximum compressive strength of 89.91 MPa. Whereas, for the other ratios of 1.5, 2.5 and 3, we have compressive strengths respectively of 83.19 MPa, 78.4 MPa and 70.4 MPa. Therefore, the optimal ratio for compressive strength is Na_2SiO_3/NaOH = 2. Beyond this ratio the compressive strength decreases. This is explained by the two following cases:

- Na_2SiO_3/NaOH = 1.5, an insufficient of NaOH for the total dissolution of aluminosilicates and an excess of Si ions in the geopolymerization. It should be noted here that silica comes from two different sources, sodium silicate and the aluminosilicate material used. The results of this study show that the insufficient quantity of Na^+ ions and the unreacting excess of Si^{4+} ions have a negative reflection on the mechanical strength of cured geopolymers [26].
- Na_2SiO_3/NaOH = 2.5 and 3, excess of Na^+ in the geopolymerization. Thus, an excess of unreacted Na^+ ions

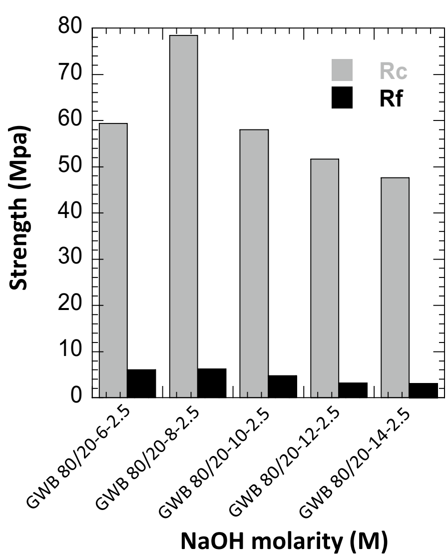

Fig. 5 Progression of compressive and flexural strength for samples prepared according to different molarities of NaOH

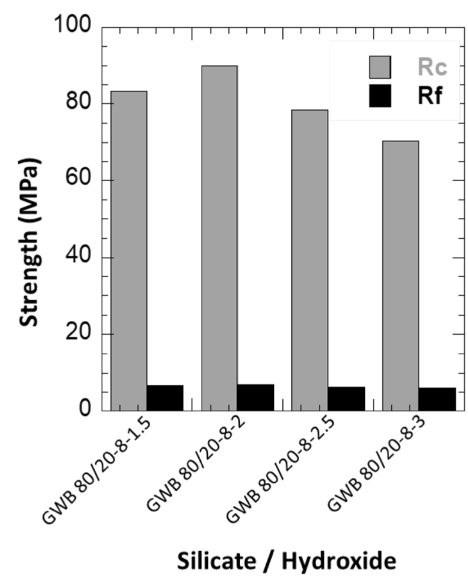

Fig. 6 Evolution of compressive and flexural strength for samples prepared according to different silicate/hydroxide ratios

which have a negative effect on the mechanical properties of the geopolymer in the cured state.

The increase in the $Na_2SiO_3/NaOH$ ratio increases the sodium content in the mixture. Sodium is important for the formation of geopolymers because it acts as charge balancing ions. However, compressive strength decreases as more silicate is added to the system because the excess sodium silicate prevents water evaporation and the formation of structures [51].

Figure 6 reveals that the ratio $Na_2SiO_3/NaOH = 2$ has the highest flexural strength value that reaches 6.94 MPa. The lowest resistance, 6.06 MPa, is given by $Na_2SiO_3/NaOH$ ratio = 3. Therefore, the optimal ratio of sodium silicate and sodium hydroxide is $Na_2SiO_3/NaOH = 2$ for flexural strength.

4.4 Optimal formulation ratio

Based on the result from the above formulation, a test with the optimal properties (8 M molarity, $Na_2SiO_3/NaOH = 2$) was performed. This test confirms the optimization of the GGBFS/WB ratio in the geopolymer formulation. The compressive and flexural strengths increase with the optimal value of NaOH molarity (8 M) and $Na_2SiO_3/NaOH = 2$ as shown in Fig. 7.

The GGBFS/WB ratio of 80/20 gives the maximum compressive strength of 89.91 MPa. Whereas, for the other ratios of 100/0, 60/40, 40/60, 20/80 and 0/100, we have respectively, 72.48 MPa, 79.2 MPa, 51.92 MPa, 44.78 MPa and 38.96 MPa.

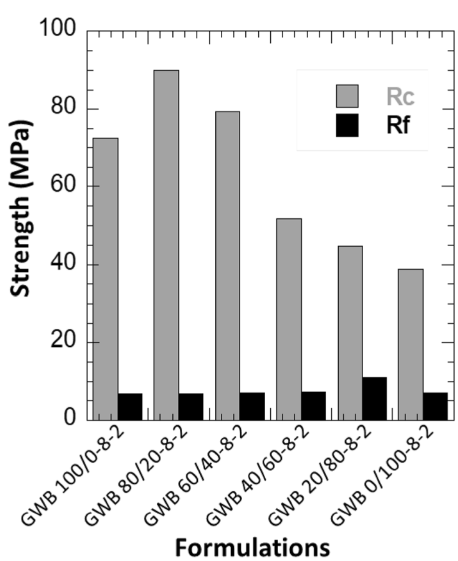

Fig. 7 Variation in compressive and flexural strength samples prepared with different GGBFS/WB ratios and optimal ratio of NaOH molarity (8 M) and the silicate-to-hydroxide ratio (S/H = 2)

The highest flexural strength value reaches 10.97 MPa given by the formulation GWB 20/80-8-2.

The results of this study reveal that the compressive and flexural strengths of geopolymer bricks samples, increases with a certain amount increase of CaO related to the GGBFS in the formulation [42]. The maximum compressive strength obtained is 89.91 MPa for the optimum value of CaO in the formulation GWB 80/20-8-2. Beyond this value of CaO the compressive strength starts to decrease. While, for the flexural resistance, the results noted that the increase occurs with the increase of the percentage of waste bricks in the geopolymer formulation. The maximum value obtained is 10.97 MPa for the formulation WB 20/80-8-2 and beyond this value, the flexural resistance decreases.

4.5 Future implementation of geopolymer bricks and recommendations

The analyses and results of this study have shown that geopolymer bricks can replace fired bricks. Future research should focus on studying the durability of this geopolymer material and the method of integrating this new generation of materials into the brick's production line. A study is being carried out on the change required in the fired brick production chain to integrate geopolymer bricks. For this practical application, several recommendations must be considered. Starting with a comparison of the life cycle phases of the two types of bricks. Then, a detailed study on the preparation of raw materials and completing it with the process of preparation and drying of geopolymer bricks at the industrial level.

5 Conclusion

This research focuses on the potential for reuse of industrial waste for the production of geopolymer-based building materials. The article presents an experimental study of waste brick recycling with the association of another industrial waste, ground granulated blast furnace slag, to produce a new geopolymer brick. The process of preparing the geopolymer bricks was carried out using a combination of hydroxide and sodium silicate as an alkaline solution. The quantity of GGBFS incorporated, the molarity of NaOH and the silicate/hydroxide ratio are the three parameters that each been optimised according to the mechanical strength of the final product. The results of this study highlight and demonstrate a new and advantageous application in the construction of a major waste with the geopolymerization process. These results show that the inclusion of ground granulated blast furnace slag (GGBFS) in the geopolymer matrix based on brick waste

(WB) improves the physical and mechanical properties of the geopolymer brick. The best compressive strength of 89.91 MPa was obtained for a ratio of GGBFS/WB = 80/20, a silicate to hydroxide ratio = 2 and a molarity of 8 M NaOH. The highest bending strength obtained in this study is 10.97 MPa for a GGBFS/WB = 20/80 ratio, a silicate to hydroxide ratio = 2 and a molarity of 8 M NaOH. This research therefore concludes that geopolymer bricks are an environmentally friendly alternative to conventional fired bricks.

Acknowledgements The author also recognizes the support of the brickworks of the north of France (BdN) for the donation of waste bricks and sand, respectively in this study.

Compliance with ethical standards

Conflict of interest This research study was followed by another study on the environmental impact of geopolymer bricks. This work presented the calculation of the CO_2 equivalent of geopolymer bricks in order to compare it with the existing fired brick. The different formulations of geopolymer bricks based on waste bricks have shown a CO_2 reduction of around 31% compared to fired bricks.

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