SUSTAINABLE UNFIRED BRICKS MANUFACTURING FROM CONSTRUCTION AND DEMOLITION WASTES

A. Seco(1)(*), J. Omer(2), S. Marcelino(3), S. Espuelas(4), E. Prieto(5)

(1) Dept. of Projects and Rural Engineering. Public University of Navarre. 31006 Pamplona, Spain. (E-mail: andres.seco@unavarra.es. Phone: +34948169682; Fax: +34948169148)

(2) Faculty of SEC, Penrhyn Road; KT1 2EE. Kingston University, London, UK. (E-mail: j.r.omer@kingston.ac.uk. Phone +44 2084172243, Fax +44 20 85477971).

(3) Dept. of Projects and Rural Engineering. Public University of Navarre. 31006 Pamplona, Spain. (E-mail: sara.marcelino@unavarra.es. Phone: +34948169224; Fax: +34948169148)

(4) Dept. of Projects and Rural Engineering. Public University of Navarre. 31006 Pamplona, Spain. (E-mail: sandra.espuelas@unavarra.es . Phone: +34948169682; Fax: +34948169148).

(5) Dept. of Projects and Rural Engineering. Public University of Navarre. 31006 Pamplona, Spain. (E-mail: epc@unavarra.es . Phone: +34948169177; Fax: +34948169148

(*)Corresponding author

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ABSTRACT

The management of construction and demolition wastes is a huge challenge for most Governments. The greatest component of such wastes is concrete and masonry fragments or remains. Among the most common approaches to valorization of such wastes is to convert them to recycled aggregates, however this may be hampered by low quality of some recycled aggregates compared to natural aggregates. This paper presents the results of experimental investigation where concrete and ceramic remains were used to partially substitute clay soil in producing unfired bricks. The bricks were then tested for mechanical strength, water absorption freeze-thaw resistance. Additionally the environmental impact of the bricks was assessed based on Life Cycle Analysis (LCA). It was established that concrete waste could be used to substitute up to 50% of the clay whereas ceramic wastes could only substitute a maximum of 30% of the clay. Blended bricks made from clay and concrete waste mixes had a lower mechanical strength than those made from clay and ceramic waste. As regards water absorption, there was no marked difference between the two blends of brick however reduction in water resistance was slightly greater in bricks containing concrete waste that in those containing ceramic wastes. Also, tests showed that freeze-thaw resistance was greater in bricks blended with concrete wastes than in those incorporating ceramic wastes. Life Cycle analyses demonstrated that it is the binder content in the mix that largely determines the environmental impact of the blended bricks.. Lastly, it was demonstrated that the most desirable technical and environmental credentials of brick material mixes resulted from using the binder combination: CL-90-S+GGBS 2/8.

KEYWORDS

Unfired bricks; construction and demolition wastes; pozzolanic reactions; mechanical properties; durability; Life Cycle Analysis.

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1. INTRODUCTION

The construction sector is of strategic importance to the global economy. In the European Union alone, construction generates about 10% of Gross Domestic Product (GDP), provides 20 million jobs and has a direct impact on the quality of life of the population (European Commission, 2014). Infrastructure and building construction and demolition activities consume about 50% of raw materials and account for 33% of 900 million tonnes of waste generated in EU each year (European Commission, 2014; Bravo et al., 2015).

There is no particular composition of Construction and Demolition Wastes (CDW) as they vary depending on the kind of structure and or demolition process and the construction management systems employed. Generally CDWs typically include: (1) concrete from superstructure, (2) bricks, tiles and ceramics from floors, roofs and partition walls and, (3) in lesser quantities, other materials like glass, wood, plasterboard, asbestos, metals, plastics or hazardous materials. The majority of these wastes are usually disposed of in landfills without any form of recovery or re-use, hence generating important economic and environmental concerns. The EU has recognized the need for a sustainable management of waste and of use of natural resources. Consequently targets have been set to increase the re-use, recovery and recycling of non-hazardous CDW across Europe above 70% by 2020, from the current average rate of 47% (European Commission, 2008; Pacheco Torgal, 2014).

There is a high potential for reuse and recycling of CDWs since most of their components can have a high resource value. As the different materials require specific ways for their valorization, the most effective management systems suggest the use of appropriate demolition techniques combined with recycling and re-use. This way glass, wood, asbestos, metals, plastics, hazardous materials, etc. can be separated, obtaining the majority of the inert waste fraction, comprising mainly concrete and masonry remains (Silva et al., 2014; Vegas et al., 2015). Such waste materials can be readily processed into Recycled Aggregates (RA) for use in place of Natural Aggregates (NA). Examples of use of RA include construction of bound /unbound pavement layers and the production of recycled concrete (Xuan et al., 2015; Özalp et al., 2016; Xuan et al., 2016). These applications are limited in practice because of the perceived lower quality and durability of RA when compared to NA. Therefore it is wide practice to exclude fine particles of RA and to limit the maximum ratio of the coarse RA fraction to the NA fraction (Bravo et al., 2015; Butera et al., 2015; Fernández Ledesma et al., 2015; Cardoso et al., 2016; Rodríguez et al., 2016; Silva et al., 2016). For example, the European Standard EN 12620 allows, for concrete manufacturing, the use of RA with a grain size above 4 mm. The Spanish Standard EHE-08 recommends 20% as the maximum ratio of RA to total coarse aggregate in the mixes used for structural concrete. Other potential ways for valorization of RA include partial substitution of natural clay soil by wastes, in the production of unfired bricks (Liu et al., 2011; Oti and Kinuthia, 2012; Miqueleiz et al., 2013; Zhang, 2013; Li et al., 2015). There are also some properties of RA that could further enhance sustainability of blended unfired bricks. For example, the finest RA fraction could be used to replace some natural materials or be used directly in the manufacture of other products, without any prior treatments. The minerals in RA may be chemically inert however the presence of any residual ceramic material can produce some pozzolanic properties (Oti et al., 2014; Schackow et al., 2015). As for the concrete element, particles could contain small quantities of residual cement that could still be reactive. Therefore this could potentially substitute for virgin binder in new construction or enable replacement of less sustainable binders like cement with more sustainable ones. (Bravo et al., 2015; Silva et al., 2016).

This research is primarily aimed at examining the suitability of using the fine fraction of CDW in the production of unfired bricks. Tests were conducted using fine materials resulting from crushed old concrete and clay bricks. Unfired brick samples were made with different dosages of five different binders. The test results were analyzed to determine: (a) the most effective binder and dosage in mix proportions that achieve target properties of the unfired bricks and (b) the environmental impact of each mix of combination.

2. MATERIALS

The soil used in this study was a grey marl from the region of Pamplona, Northern Spain. Table 1 shows the chemical characterization of the soils and CDW fine fraction. Mineralogical compositions were estimated using X Ray Diffraction (XRD) analysis based on the chart proposed by Al-Rawas (1999). Using X Ray Fluorescence (XRF) analysis the soil compositions were expressed in terms of the most predominant or influential oxides.

TABLE 1

According to the Spanish Standards UNE 103104 and UNE 103103, the material has typical plastic limit (PL) of 18% and a liquid limit (LL) of 26%. Therefore based on Casagrande Classification, this soil belongs to class CL, which is a low-plasticity clayey silt. From a mechanical point of view it is a low load-bearing capacity soil, which limits its possibilities of use as a construction material. To carry out this investigation, one tonne of the natural marl was extracted and, after homogenization of the sample, it was crushed to a maximum particle size of 1 mm.

The concrete fine fraction, which was supplied by a recycling plant in Vitoria, Northern Spain, was obtained by crushing old structural concrete. The recycling plant only valorizes the fraction 40-100 mm as RA, while any finer particles are disposed of in a landfill. For this investigation, a sample weighing 100 kg and with a maximum particle size of 4 mm was prepared by sieving the 0-40 mm fraction. The ceramic fine fraction was also obtained from the same recycling plant. In this case, to avoid contamination of the CDW by components such as plaster, mortar, etc., whole sized bricks were selected, crushed and sieved in laboratory to below 4 mm size.

In this investigation four additives were considered for use as binder components: (i) Portland Cement (PC), (ii) Calcareous Hydrated Lime (CL-90-S), (iii) Natural Hydrated Lime (NHL-5) and (iv) Ground Granulated Blast furnace Slag (GGBS). The PC used in this study was manufactured in accordance with the European Standard EN 197–1 and is marketed in Spain under the trade name CEM I 52.5 N. Table 1 shows the composition of all the additives, expressed in terms of their main oxides based on XRF analysis.

TABLE 2

Table 2 also shows the embodied CO_2 and energy, as defined by Grist el al. (2015). Two different types of lime were used in this study: (1) A Natural Hydraulic Lime (NHL-5), obtained from burned non-pure limestone and manufactured in accordance with the European Standard EN 459–1. This Lime has hydraulic properties due to the presence of Aluminum and Silicon oxides as well as free Calcium. (2) A calcareous hydrated Lime (CL-90-S) obtained from burned pure limestone and manufactured in accordance with the European Standard EN 459–1. GGBS is a by-product obtained during the manufacturing of pig iron and has a high cementitious potential due to its richness in Calcium, Silicon and Aluminum oxides. The GGBS was combined with the CL-90-S lime as activator, at different ratios. Table 3 shows the binder combinations and the dosages tested, expressed as binder percentage of the total brick weight.

TABLE 3

3. METHODS

Prior to the production of the samples the maximum possible ratio of substitution of the marl soil by each CDW was determined, based on workability requirements as per Spanish Standard UNE 41410 (AENOR, 2008). For the concrete fine fraction the maximum substitution rate was determined to be 50% of the soil whereas for the ceramic waste it was 30%. Once the rates of substitution for each kind of wastes were defined, laboratory specimens were prepared according to the method outlined by Seco et al. 2017. For each combination soil, CDW and additives were mixed for 10 minutes to obtain a completely dry and homogeneous mixture. Then the quantity of water corresponding to the pre-determined optimum moisture content was gradually added to the mixture. The ingredients were then thoroughly mixed to a homogeneous state. The wet mixes were then hydraulically compacted in a cylindrical mold using 9 MPa pressure to produce specimens of 65mm diameter and 75mm height. To prevent further moisture losses the specimens were covered with polythene sheeting and cured in a wet chamber until the testing ages of 1, 7, 14, 21 and 28 days.

After curing, the samples were tested for Unconfined Compressive Strength (UCS) in accordance with the Spanish standard UNE 103400, before and after 24 hours of immersion in water. Measurements of water absorption (WA) after 24 hours of submersion were carried out in accordance with the European Standard EN 771-1.

Also, Thawing and freeze-thaw tests were carried out on the samples in accordance to the Spanish standard UNE 67028 EX. For this test, prismatic samples of dimensions 225x110x60 mm were subjected to 25 cycles of freezing at -8ºC during 5 hours and thawing at 15ºC for 1 hour.

In order to quantify the Environmental impact of each mix, a Life Cycle Analysis (LCA) was carried out based on the approach presented by (Marcelino-Sadaba et al., 2017). The impacts evaluated include CO_2 emissions and embodied energy, which were analysed based on Grist et al. (2015) methods.

4. RESULTS AND DISCUSSION

4.1. UNCONFINED COMPRESSIVE STRENGHT

Figure 1 shows the results obtained for the UCS tests for the various curing times and binder types, for the mixtures where the marl soil was partially replaced by concrete waste.

FIGURE 1

The reference line corresponds to the UCS result obtained for 28 days curing period for the mixes where pure marl soil was treated with 10% of PC. In this case the reference UCS value is 8.60 MPa. For the concrete combinations the worse results corresponded to the CL-90-S samples, where there were insignificant UCS differences between the mixes containing different dosages. The variations of UCS with curing time were very small, the best result being 2.70 MPa for a lime content of 4% and curing time of 28 days. The UCS values for NHL-5 were higher, such that with 10% of additive 3.90 MPa was reached at 28 days test age. . With this additive, there was a more discernible pattern of UCS increase with time as compared to the case of CL-90-S additive. This was observed at all dosages of the additive. The mixes containing PC and 10% of additive reached a maximum UCS of 7.45 MPa at 28 days. A clear pattern of UCS development was also observed as curing time and dosage increased, with rapid rate of UCS increase during the first 14 days of curing. CL-90-S+PC combinations produced UCS values intermediate between those of mixes containing one of the binders on its own. For mixes with these binders, the resistance improved as the PC content in the binder increased. Thus, CL-90-S+PC 2/8 achieved the highest result at 6.85 MPa for 28 days of curing. The best UCS result among all the combinations tested was 12.75 MPa, which was obtained in the CL-90-S+GGBS 2/8 samples after 21 days of curing. Mix combinations richer in GGBS produced the best results for the above binders and in general the most significant UCS increase occurred before 21 days age.

The UCS results from lime treated target mix CL-90-S lime highlight the low reactivity of the marl and concrete aggregates and the low content of reactive Silicon and Aluminum oxides. Not surprisingly, binders richer in these oxides had greater UCS values. Mixe combinations: 2/8 CL-90-S+GGBS, 10% PC and 2/8 CL-90-S+PC being richest in PC and GGBS, hence reactive Silicon and Aluminum, showed the strongest cementing properties.

Figure 2 shows the UCS results when marl soil was partially replaced by ceramic waste and treated with the different binders.

FIGURE 2

In the case of this target combination, an increase in resistance with increasing curing period was observed. At 28 days, a dosage of 10% in CL-90-S produced a UCS value of 6.8 MPa. In the case of NHL-5, a dosage of 8% produced the maximum UCS value of 7.65 MPa, at 28 days. For the mix with PC, UCS reached 8.95 MPa for the 10% dosage at 28 days, thereby exceeding the reference value for the marl soil. As occurred in the concrete based target mix, CL-90-S+PC 2/8 combination produced the best result for this kind of binder, with UCS of 7.85 MPa at 28 days. For this target, the best UCS results were also obtained in the samples treated with CL-90-S+GGBS 2/8 binder, where the UCS was 12.65 MPa at 28 days. As occurred in the concrete-based target, with this kind of binders, the best results were obtained with the highest GGBS contents.

NHL-5 and CL-90-S attained higher UCS compared to the concrete based target mixes. Both additives showed increasing resistance with curing time. In general, this target mix when blended with binders richest in Calcium produced higher 7-day UCS values in comparison to concrete based mixes. This demonstrates the pozzolanic property of the ceramic waste owing to availability of free Silicon and Aluminum.

Figures 3 and 4 illustrate the percentage UCS loss when the samples were tested after 24 hours of immersion in water.

FIGURE 3

FIGURE 4

In the case of the concrete based target mixes, with CL-90-S, a loss of UCS between 40% and 60% occurred for all the dosages and for all the curing periods. The pattern was similar in NHL-5 but the loss of resistance varied from 30% to 55%. Mixes combinations with PC also showed a clear loss of resistance for all curing periods exceeding 7 days. The final loss values were between 16 and 40%. For 1 day age, the strength losses for the PC mixes were lower and, for the 10% dosage, an increase of 3.3% of UCS was observed. The CL-90-S+PC combinations also showed a general loss of resistance after 24 hours of immersion in water with final values being between 13% and 44%. The CL-90-S+GGBS combinations showed a similar pattern to the PC ones. At the age of 1 day, the mix combination 2/8 CL-90-S+GGBS showed an increase of UCS of 41%, whereas the 4/6CL-90+GGBS and the 6/4CL-90+GGBS had increases of 27% and 4% respectively. For the 8/2 combination a loss of 8.1% was obtained. In all the CL-90-S+GGBS combinations, the final UCS values showed a loss of resistance between 12% and 35%.

In the case of the ceramic based target combination mixes, the pattern of UCS loss was similar to the concrete based target ones, but with lower absolute loss values. Mixes with CL-90-S had a loss of UCS of between 19% and 43%, for all the curing periods. For NHL-5 the losses varied from 7% to 35%. PC also showed a lower loss of UCS for 1 day curing period. At 28 days age, PC samples showed a loss of resistance of between 10% and 23%. CL-90-S+PC combinations also showed lower losses of UCS at 1 day but for longer curing times the percentage UCS losses increased and were between 18% and 24% for 28 days of curing. CL-90-S+GGBS combination mixes aged 1 day showed increase in UCS values such that, for combination 6/4, the increase was 28%. At 28 days age, the CL-90-S+GGBS combination mixes showed losses of resistance of between 13% and 27%.

The ceramic waste based target mixes showed less sensitivity of UCS to immersion in comparison to the concrete based target mixes. The behavior of the binders in both target mixes was similar. The anomalous UCS losses, and even increases, observed in some of them at the age of 1 day is thought to be due to the effect of the free calcium available on flocculation of the marl and hydration hence a cementing behaviour. Binders such as PC or GGBS, which are rich in Aluminum and Silicon oxides, have lower free Calcium contents. Therefore their flocculation potential is lower and thus the loss of soil cohesion and resulting UCS loss are also lower. In addition, Figures 1 and 2 show how, at 1 day of age, pozzolanic reactions would have already started for binders containing PC or GGBS. . As such, cementation processes could also justify the lower loss of UCS within the first day.

4.2. WATER ABSORPTION

Figure 5 shows the water absorption test results of the concrete based target samples.

FIGURE 5

CL-90-S and NHL-5 combinations had steady water absorption values of between 13.8% and 16.0% (but mostly close to 15%) for all curing periods. PC combinations showed different behavior depending on the dosage and curing time. The water absorption at 28 days was approximately 13% for all the dosages. At the age of 7 days, combinations having 8% and 10% dosages showed water absorption values of 16.0% and 14.8% respectively, whilst the result for the 6% dosage PC combination was 10.3%. These differences terminated at the age of 14 days when the three combinations exhibited very similar values of water absorption. New differences were observed at the age of 21 days when the combination of 6% PC yielded 11.84%, 8% PC gave 11.5% and 10% PC showed 11.2% water absorption. This is an opposite pattern to that seen for 14 days cured samples. All the CL-90-S+PC combinations gave water absorption values of between 13% and 16% at all the curing times. These combinations showed an inverse PC dosage-water absorption relationship except for the 2/8 combination at the ages of 1 and 7 days. CL-90-S+GGBS combinations reached final values between 11-14% of water absorption. In these combinations the changes in water absorption with curing time followed two different patterns: 2/8 and 4/6 combinations on the one hand and 6/4 and 8/2 on the other hand. Binder combinations 2/8 and 4/6 showed the lowest water absorption values at the age of 14 days with the results being 9.3% and 10.2% respectively.

The water absorption values obtained for this target do indicate a definitive trend of variation with either curing time or richness of the binder in Calcium, Aluminum and Silicon. This could be due to complex hydration processes of these binders.

Figure 6 shows the water absorption test results of the ceramic based target samples.

FIGURE 6

In this case, water absorption values were higher than in the concrete based target. Thus, CL-90-S and NHL-5 combination mixes achieved final values varying between 16.7-18.4% and 16.3-18.4% respectively. PC samples yielded results lying in the range 15.4% to 17.4%, CL-90-S+PC gave 16.5% to 18.4% and CL-90-S+GGBS produced 12.9% to 15.3%. Like with the concrete based binder, the ceramic based binder did not show any clear patterns here. In addition, some of the PC, CL-90-S+GGBS and CL-90-S+PC combination mixes displayed anomalous absorption values at intermediate curing ages. These are also likely to be attributable to the hydration process of the binders as well as the formation of pozzolanic gels in the mixes.

4.3. THAWING AND FREEZING TEST

Subsequent to the UCS and water absorption tests, one combination of each target mix with a binder was e selected for freeze-thaw testing. The selection criteria were based on findings by Seco et al. (2017) which demonstrated a distinct relationship between unconfined compressive strength (UCS) and durability of unfired bricks.

As freeze-thaw tests are usually considered an indicator of durability, it was imperative that the selection of the test mix considered mechanical properties before and after 24 hours of immersion in water. Therefore, for the concrete based target mix, the reasonable selection was CL-90-S+GGBS 2/8. The binder in this case was chosen with regards to the low reactivity of the target mix, which required use of rich binders to enhance the properties of the brick product. The combination 2/8 produced the best overall UCS, water resistance and water absorption. In the case of the ceramic waste blended material, the mix combination NHL-5 10% was chosen so as to exploit the reactivity of the target mix hence avoid the use of other binders richer in Silicon and Aluminum oxides. The 10% target combination had an adequate UCS and highest water resistance.

FIGURE 7

After the 25 freeze-thaw, the test samples were visually inspected for any surface damage, in accordance with the UNE 67028 EX standard. Figure 7 shows representative damages observed in the two target combinations. In the concrete based target with CL-

90-S+GGBS 2/8, 100% of the specimens had small surface cracks on the smallest side of the bricks. In contrast, the ceramic based target specimens with 10% of NHL-5 showed general damages on all the faces of the bricks in all cases. They showed “scale” damage pattern of approximately 2 mm, possibly caused by water permeation and freeze induced cracks.

This scale damage extent was not avoided by any of the combination mixes and thus no other combinations were tested.

4.4. ENVIRONMENTAL IMPACT EVALUATION OF THE DIFFERENT COMBINATIONS

Figure 8 shows the environmental impact of the production of each brick material combination based on their embodied energy and CO_2 emissions. As a reference, calculations included the environmental impact of bricks made of pure marl soil treated with 10% of PC.

FIGURE 8

Figure 8 shows how the absolute impact of any combination mix depends mainly on the binder dosage and production nature (hence the embodied energy and CO_2 emissions). Both concrete and ceramic wastes have zero environmental impacts and also the marl soil has very little therefore the unfired bricks from these wastes have no manufacture related environmental impact. The highest absolute impact is shown by mix combinations richest in PC while the ones richest in GGBS have the lowest impact values. The target mix combination made of concrete waste treated with 10% of PC reached 94.80 kg of CO_2 and 425 MJ. The target mix combination comprising ceramic waste with CL-90-S+GGBS 2/8 gives 21.16 kg of CO_2 and 214.14 MJ per tonne.

FIGURE 9

Figure 9 shows the results obtained when the environmental impact relative to UCS is considered. In this case CL-90-S richest combinations show adverse values because of their low mechanical properties and the relatively high production impact of this binder. In this case, the highest values correspond to the target mix combination made of ceramic waste with 10% of CL-90-S, which gives 30.79 kg of CO_2/MPa of UCS and 152.39 MJ/MPa. The most favorable impact once again corresponds to the mixes richest in GGBS. The best target mix combination incorporating concrete waste with CL-90-S+GGBS 2/8 gave 1.71 kg of CO_2/MPa of UCS and 17.27 MJ/MPa per tonne.

5. CONCLUSIONS

This experimental investigation demonstrated how concrete and ceramic CDWs fine fractions, as substitutes for natural marl soil, modified the target physical properties and the chemical reactions that occur in the unfired bricks. The maximun rate of substitution for each waste type was different because of the workability requirements for the mixes manufacturing. Thus, for the concrete CDW the maximum substitution rate was 50%, meanwhile for the ceramic CDW, a substitution rate up to 30% was possible. In the case of the concrete based target, UCS at the age of 28 days decreased 13.4% in relation to the pure soil, when both combinations were treated with 10% of PC. In the case of the ceramic based target, the final UCS value when the same binder and dosage where used, overtook the reference value by 4.1%, demonstrating a higher chemical reactivity of the ceramic waste by comparison to the concrete based one.

UCS test after 24 hours of immersion in water showed a lower sensitivity of the ceramic waste target than the concrete based one. Both kind of targets showed a lack of a clear UCS losses trend as well as anomalous values at intermediate curing ages. This is due to complex flocculation-hydration-cementation processes in the different combinations as well as to the modification of the target physical properties.

Both trial wastes yielded similar final values of water absorption despite the different substitution rates. At intermediate curing ages ceramic combinations showed changes in water absorption because of the hydration process of the binders. Although in concrete combinations, the UCS losses after 24 hours of immersion in water were much higher than in the ceramic ones, the freeze/thaw performance was better. These results show the complexity of the relationships between mechanical properties, water absorption and durability as key parameters for the characterization of these kinds of materials. This highlights that test results have to be carefully interpreted for a correct characterization of this kind of construction materials from a technical point of view.

LCA showed the environmental impact of each combinations based on the CO_2 released and the energy consumed during the whole production process. Combinations environmental absolute impacts mainly depend on the binders manufacturing impacts and dosage. The target kind effect is based only on the substitution of the natural soil by the CDWs. Thus, combinations based on Portland Cement resulted to have the biggest absolute impacts either CO_2 emissions or embodied energy meanwhile the lower results corresponded to the GGBS richest combinations. If the mechanical properties of each combination are taken into account, CL-90-S arises as the worst environmental binder while GGBS got the smaller impacts per strength unit (MPa). LCA analysis allowed to quantify the impact related to each combination manufacturing but it did not allowed to consider the additional environmental benefits of the substitution of a no renewable resource as is the natural soil by a recycled target.

The global conclussion of this investigation is that the substitution of a natural soil by recycled targets modifies the target-binder chemical reactions. This could be taken into account for the optimization of the target formulation and binder kind and dosage selection to optimize the unfired brick manufacturing from technical and environmental points of view.

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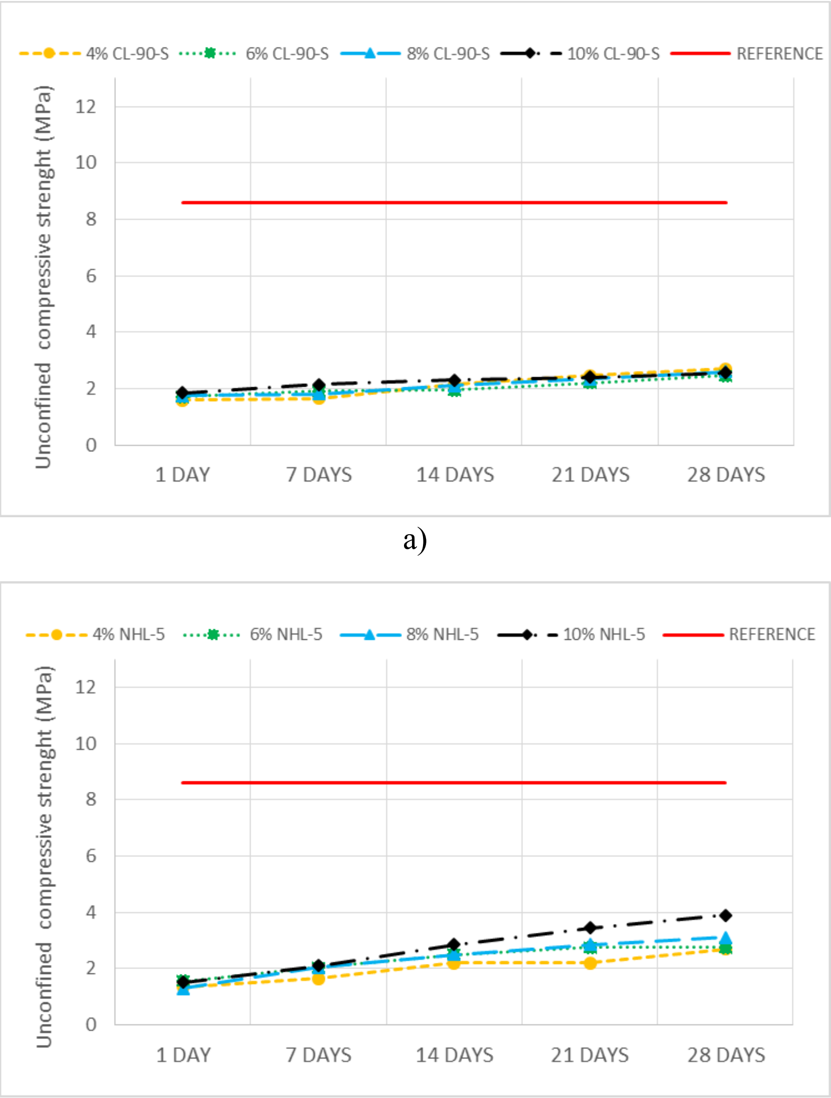
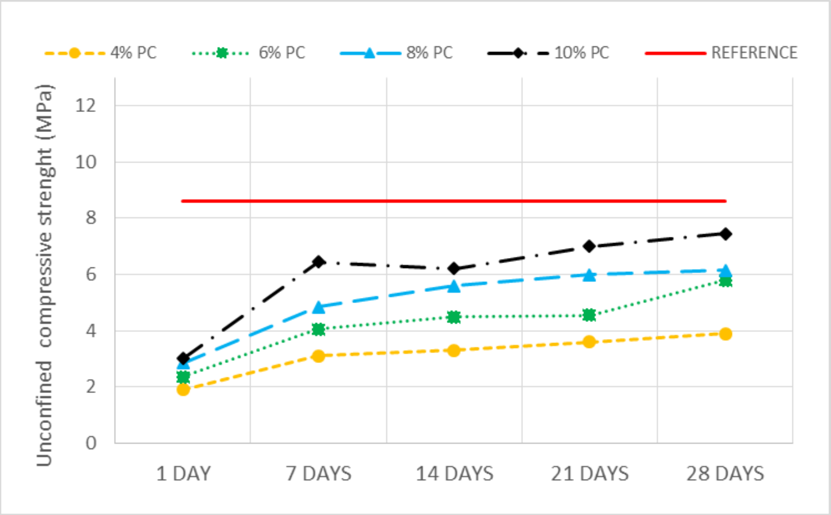
FIGURES

FIGURE 1. Unconfined compressive strength results for the different considered combinations based on concrete waste substitution.

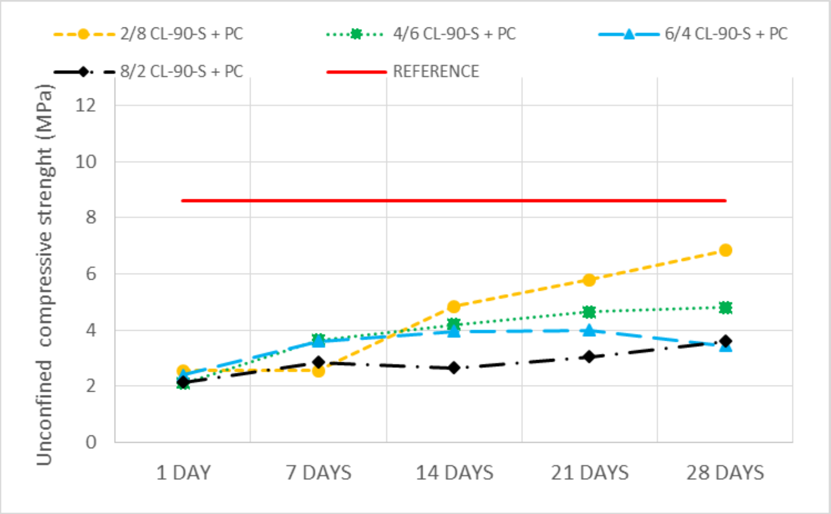


a)

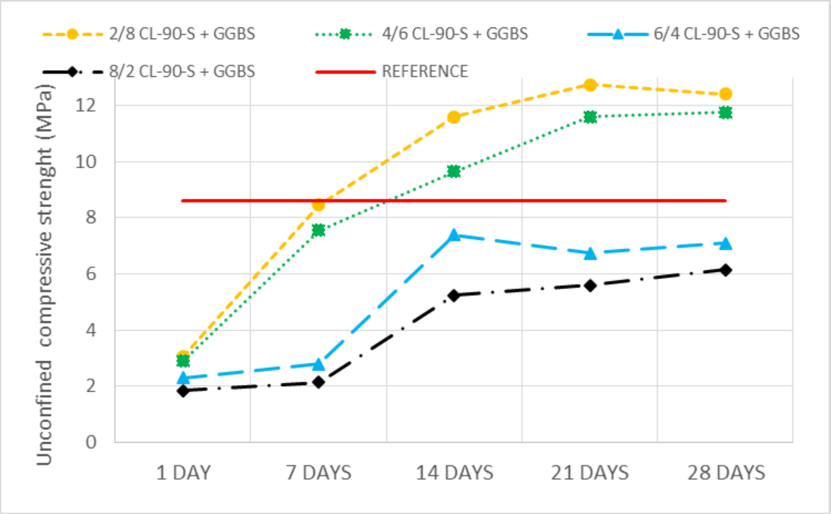
b)


4% PC
6% PC
8% PC
10% PC
REFERENCE
Unconfined compressive strenght (MPa)
0
2
4
6
8
10
12
1 DAY
7 DAYS
14 DAYS
21 DAYS
28 DAYS

c)

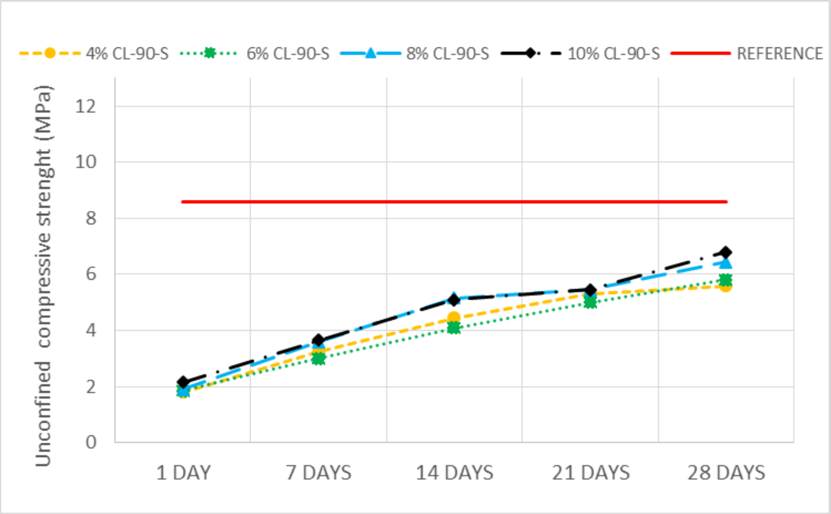

2/8 CL-90-S + PC
4/6 CL-90-S + PC
6/4 CL-90-S + PC
8/2 CL-90-S + PC
REFERENCE
Unconfined compressive strenght (MPa)
0
2
4
6
8
10
12
1 DAY
7 DAYS
14 DAYS
21 DAYS
28 DAYS

d)


2/8 CL-90-S + GGBS
4/6 CL-90-S + GGBS
6/4 CL-90-S + GGBS
8/2 CL-90-S + GGBS
REFERENCE
Unconfined compressive strenght (MPa)
0
2
4
6
8
10
12
1 DAY
7 DAYS
14 DAYS
21 DAYS
28 DAYS

e)

FIGURE 2. Unconfined compressive strength results for the different considered combinations based on ceramic waste substitution.



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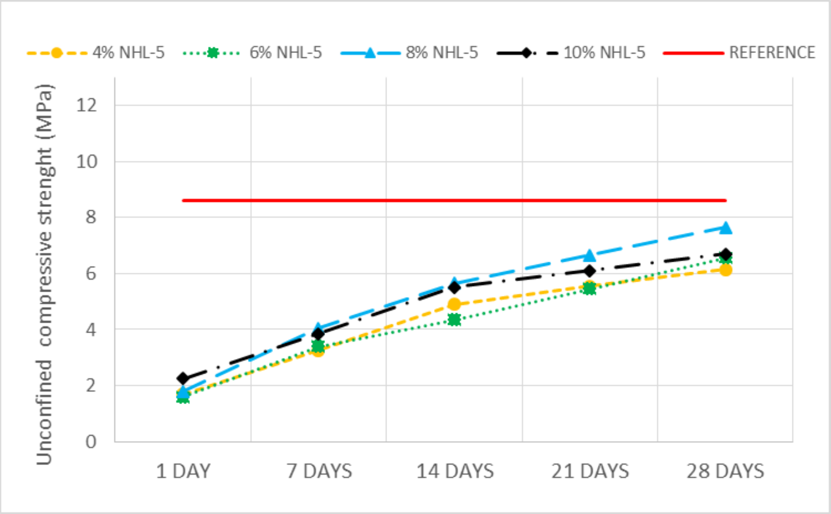

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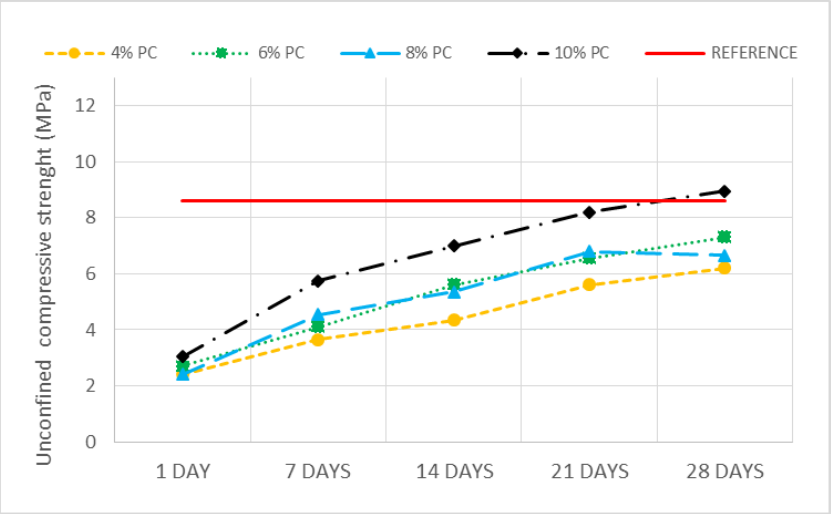
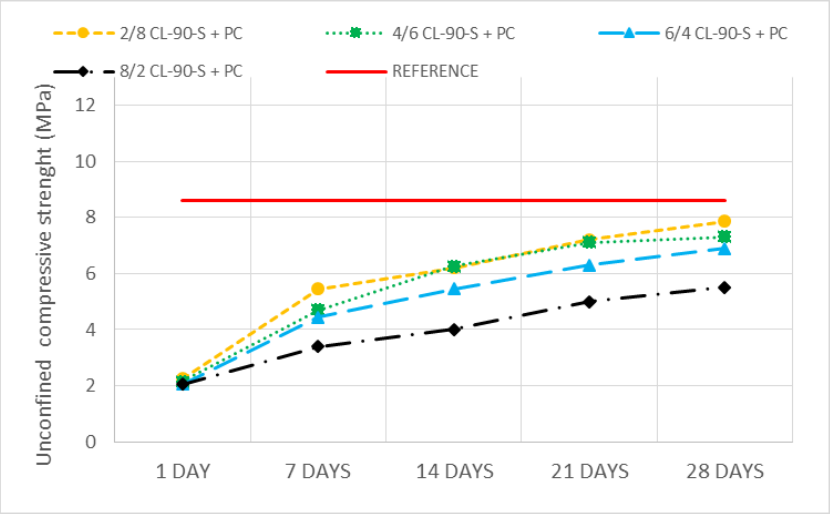
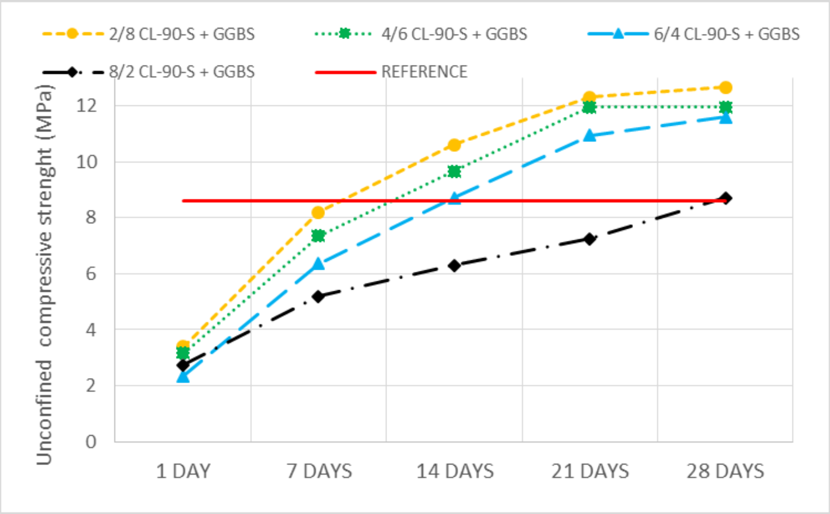


c)

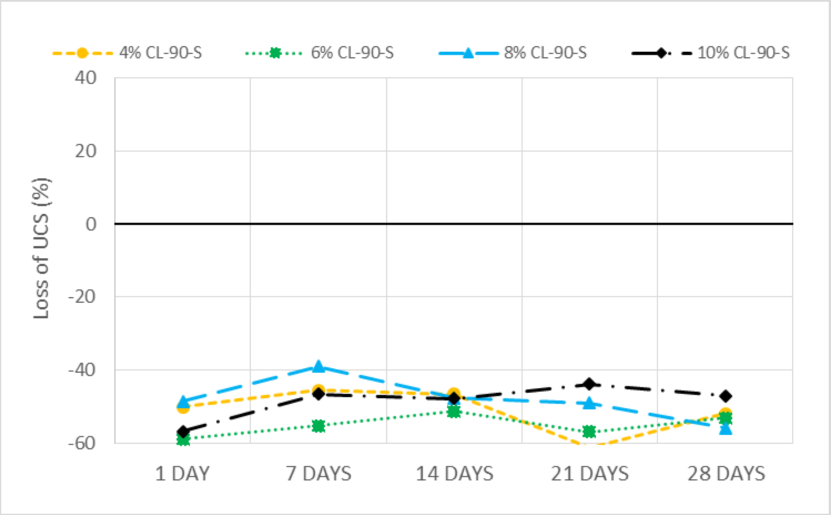


d)

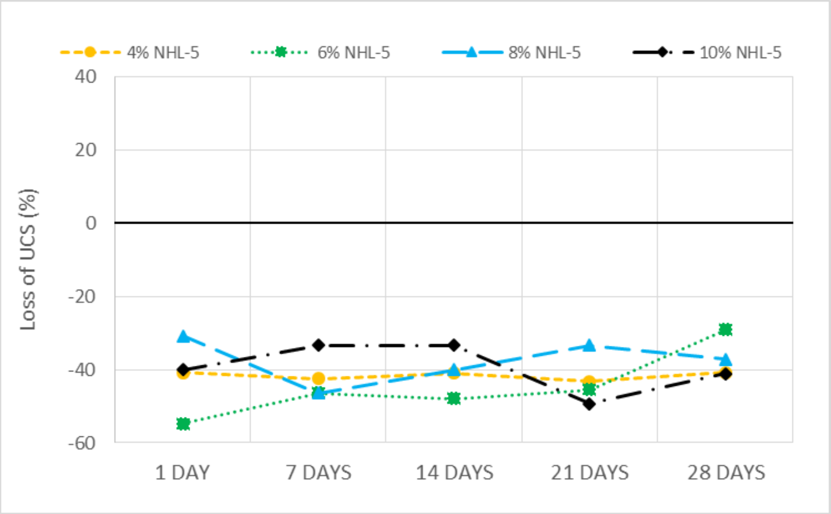


e)

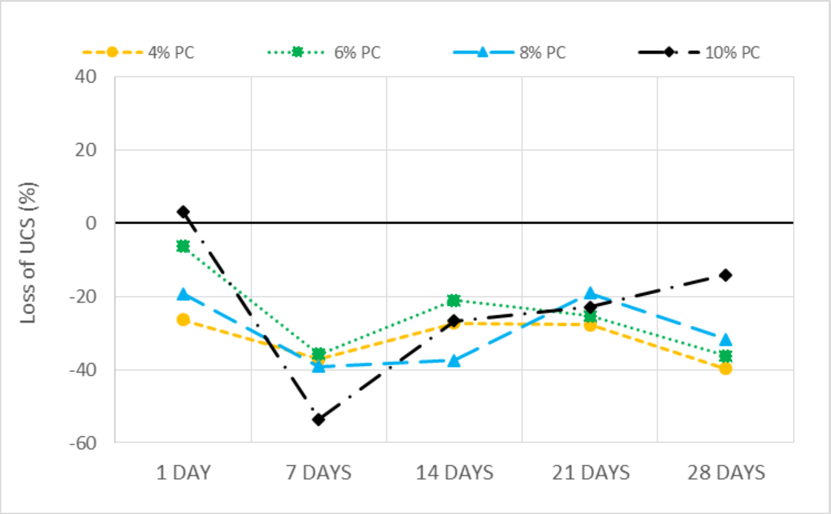
FIGURE 3. Unconfined compressive strength results for the different considered combinations based on concrete waste substitution after 24 hours of water immersion.


4% CL-90-S
6% CL-90-S
8% CL-90-S
10% CL-90-S
Loss of UCS (%)
40
20
0
-20
-40
-60
1 DAY
7 DAYS
14 DAYS
21 DAYS
28 DAYS

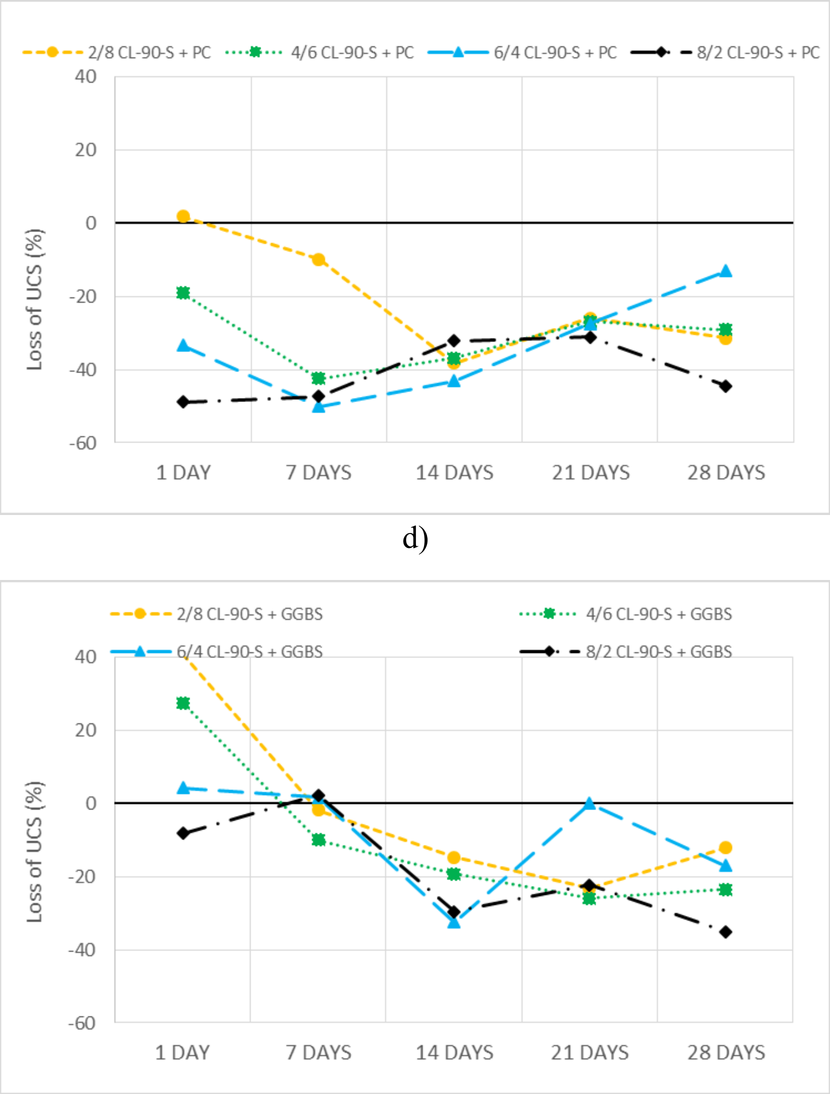
a)


4% NHL-5
6% NHL-5
8% NHL-5
10% NHL-5
Loss of UCS (%)
40
20
0
-20
-40
-60
1 DAY
7 DAYS
14 DAYS
21 DAYS
28 DAYS

b)


4% PC
6% PC
8% PC
10% PC
Loss of UCS (%)
40
20
0
-20
-40
-60
1 DAY
7 DAYS
14 DAYS
21 DAYS
28 DAYS

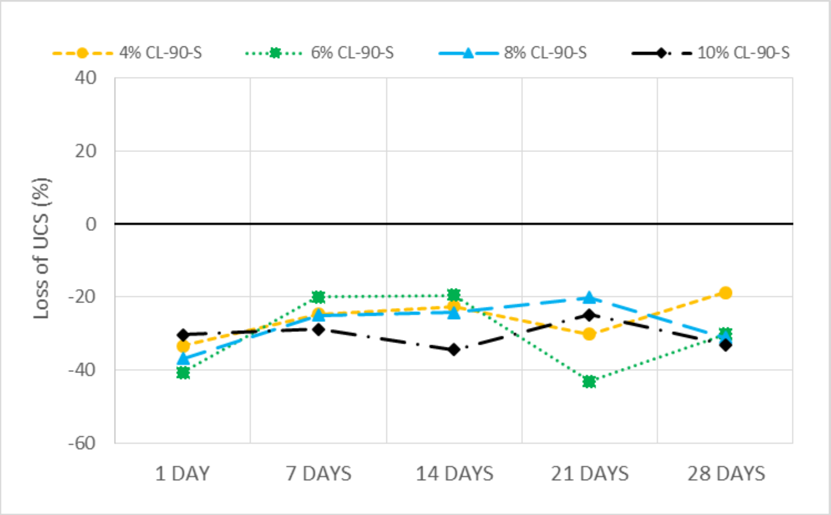
c)



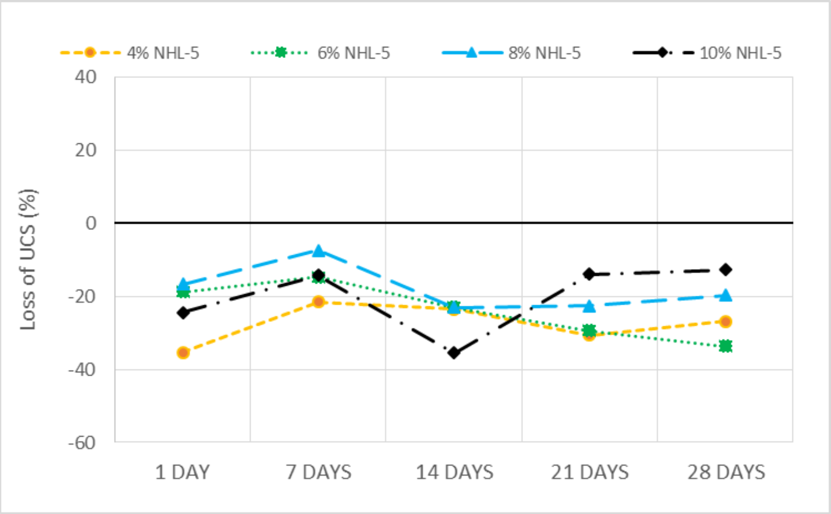
d)

e)

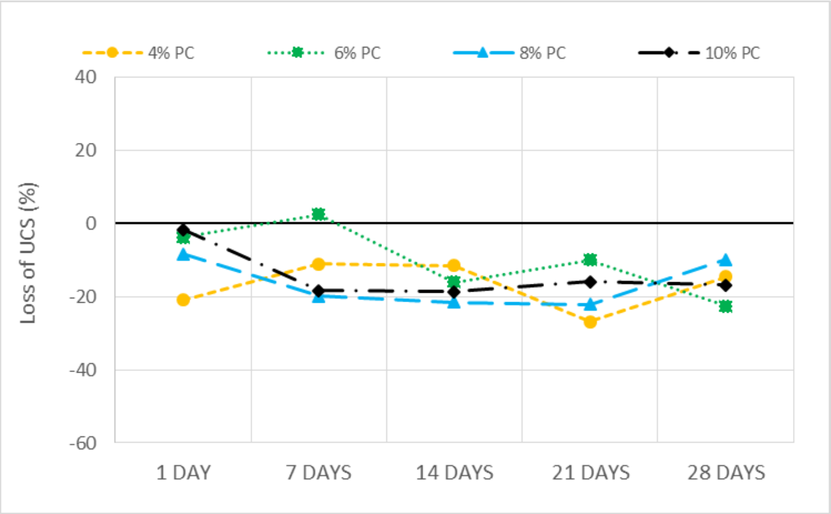
FIGURE 4. Unconfined compressive strength results for the different considered combinations based on ceramic waste substitution after 24 hours of water immersion.


4% CL-90-S
6% CL-90-S
8% CL-90-S
10% CL-90-S
Loss of UCS (%)
40
20
0
-20
-40
-60
1 DAY
7 DAYS
14 DAYS
21 DAYS
28 DAYS

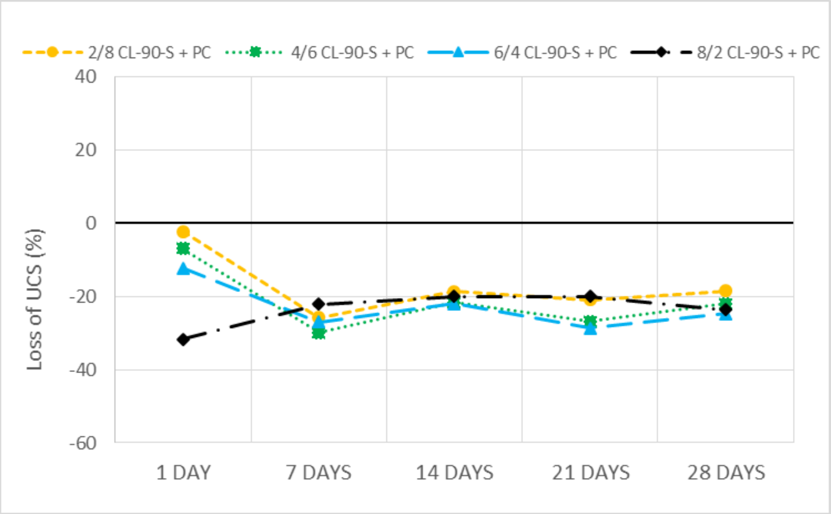
a)


4% NHL-5
6% NHL-5
8% NHL-5
10% NHL-5
Loss of UCS (%)
40
20
0
-20
-40
-60
1 DAY
7 DAYS
14 DAYS
21 DAYS
28 DAYS

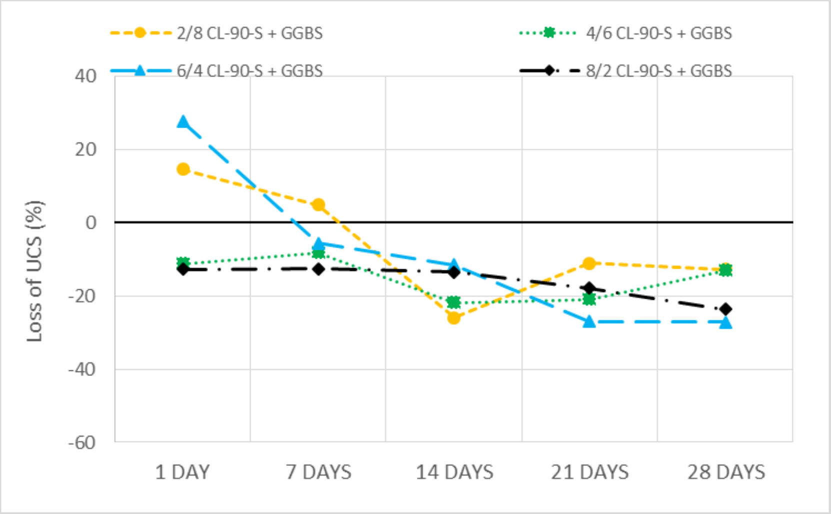
b)


4% PC
6% PC
8% PC
10% PC
Loss of UCS (%)
40
20
0
-20
-40
-60
1 DAY
7 DAYS
14 DAYS
21 DAYS
28 DAYS

c)

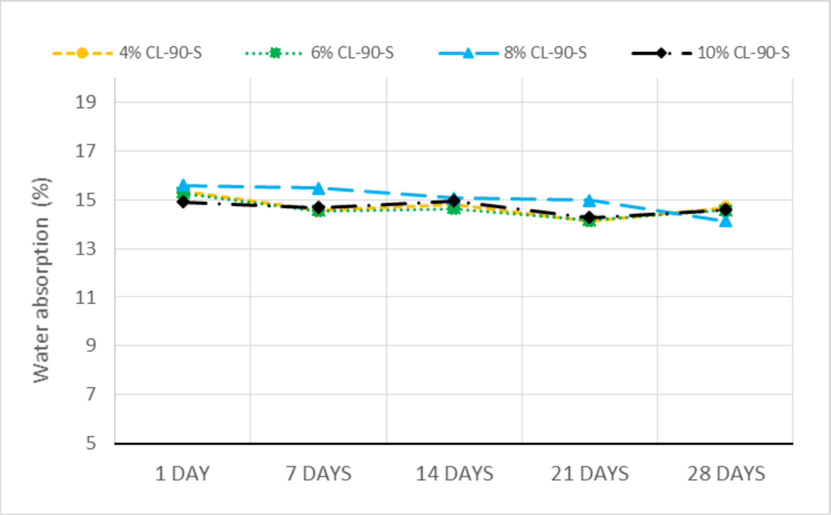


d)

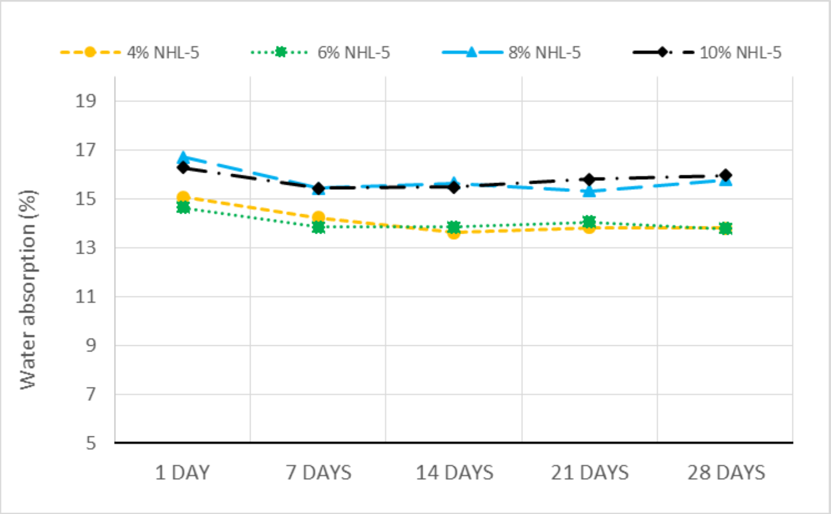


e)

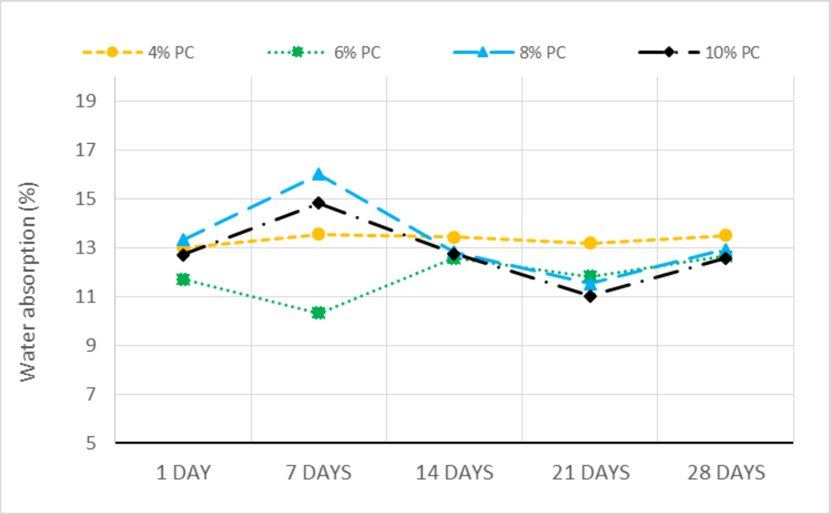
FIGURE 5. Water absorption test results for the different considered combinations based on concrete waste substitution after 24 hours of water immersion.


4% CL-90-S
6% CL-90-S
8% CL-90-S
10% CL-90-S
Water absorption (%)
19
17
15
13
11
9
7
5
1 DAY
7 DAYS
14 DAYS
21 DAYS
28 DAYS

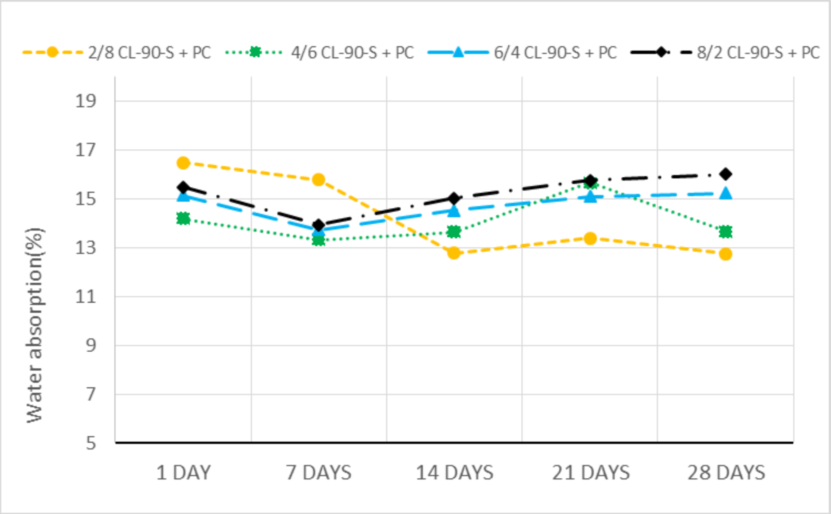
a)


4% NHL-5
6% NHL-5
8% NHL-5
10% NHL-5
Water absorption (%)
19
17
15
13
11
9
7
5
1 DAY
7 DAYS
14 DAYS
21 DAYS
28 DAYS

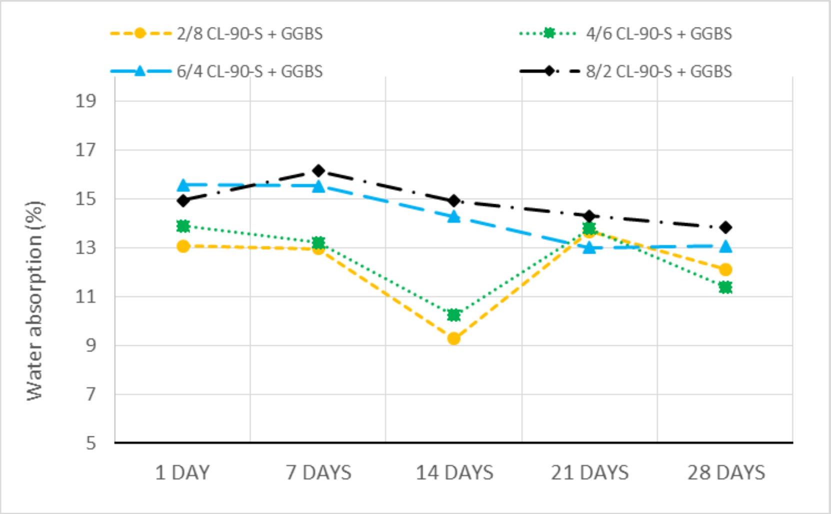
b)


4% PC
6% PC
8% PC
10% PC
Water absorption (%)
19
17
15
13
11
9
7
5
1 DAY
7 DAYS
14 DAYS
21 DAYS
28 DAYS

c)

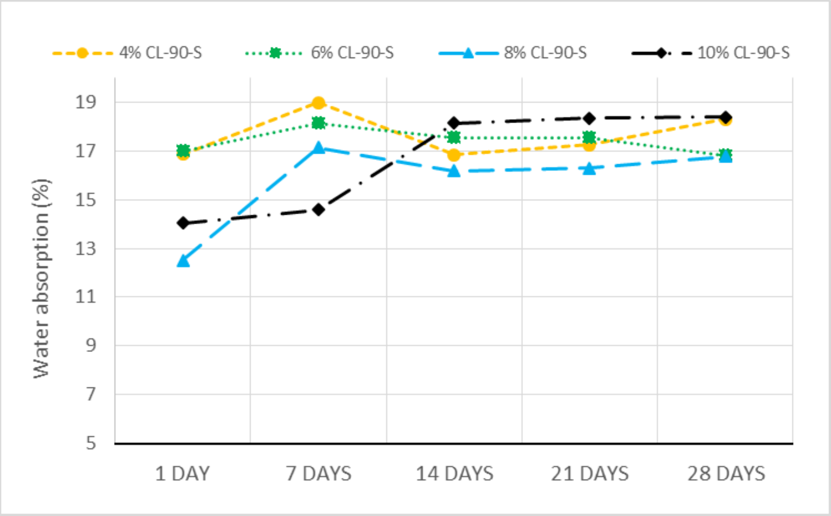


d)

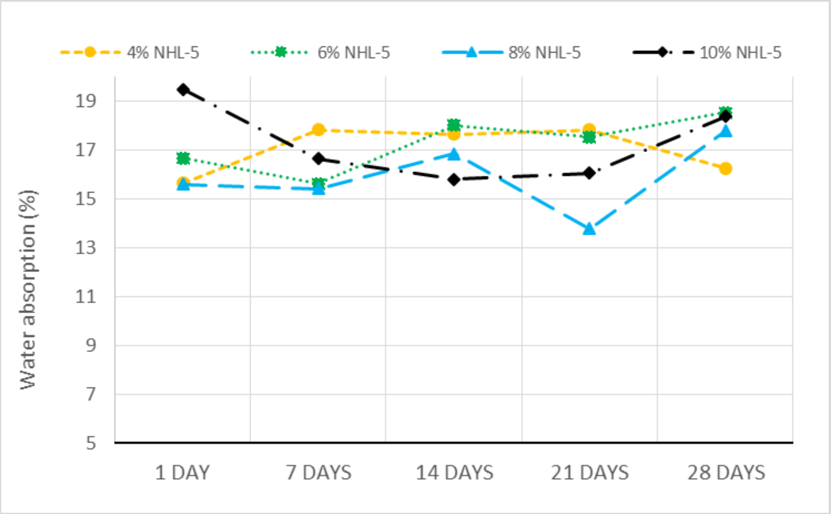


e)

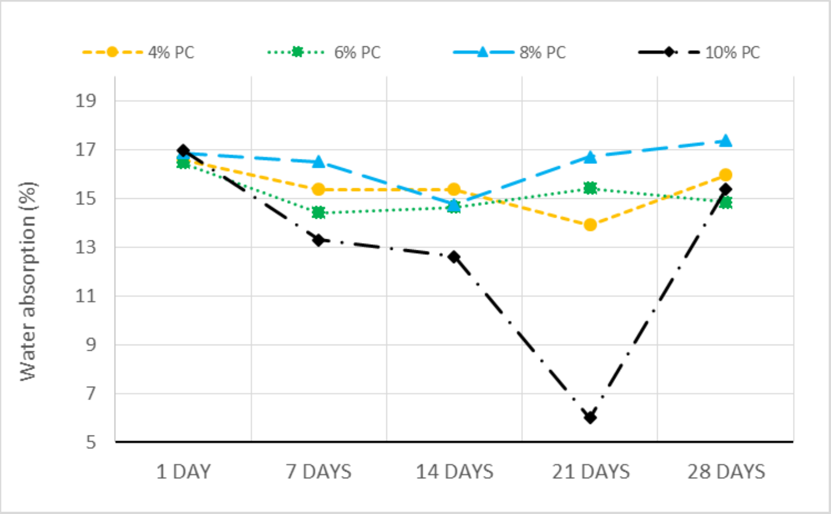
FIGURE 6. Water absorption test results for the different considered combinations based on ceramic waste substitution after 24 hours of water immersion.



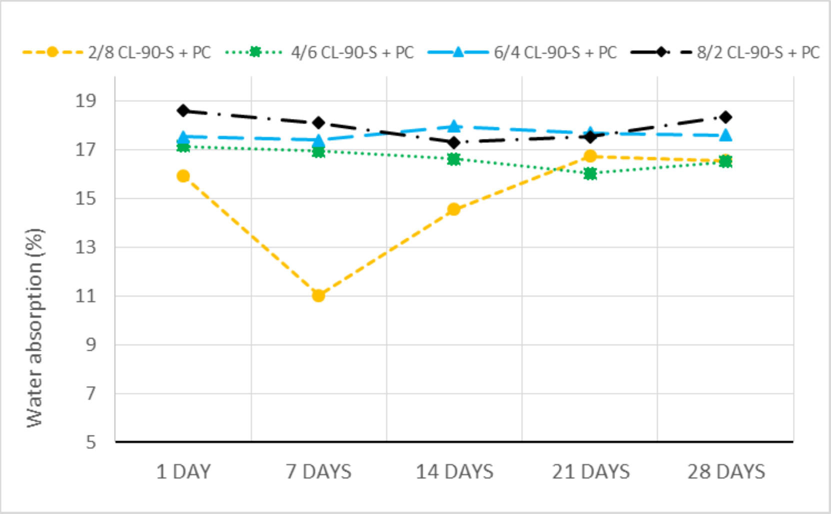
a)


4% NHL-5
6% NHL-5
8% NHL-5
10% NHL-5
Water absorption (%)
19
17
15
13
11
9
7
5
1 DAY
7 DAYS
14 DAYS
21 DAYS
28 DAYS

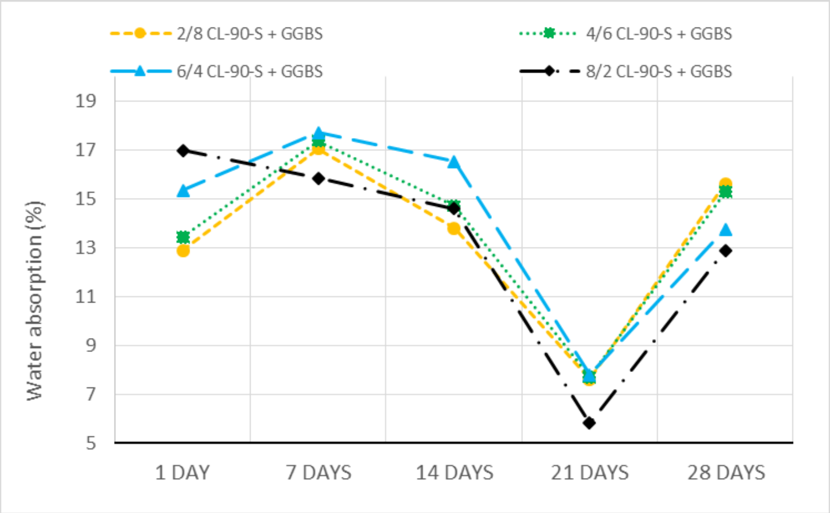
b)


4% PC
6% PC
8% PC
10% PC
Water absorption (%)
19
17
15
13
11
9
7
5
1 DAY
7 DAYS
14 DAYS
21 DAYS
28 DAYS

c)


2/8 CL-90-S + PC
4/6 CL-90-S + PC
6/4 CL-90-S + PC
8/2 CL-90-S + PC
Water absorption (%)
19
17
15
13
11
9
7
5
1 DAY
7 DAYS
14 DAYS
21 DAYS
28 DAYS

d)

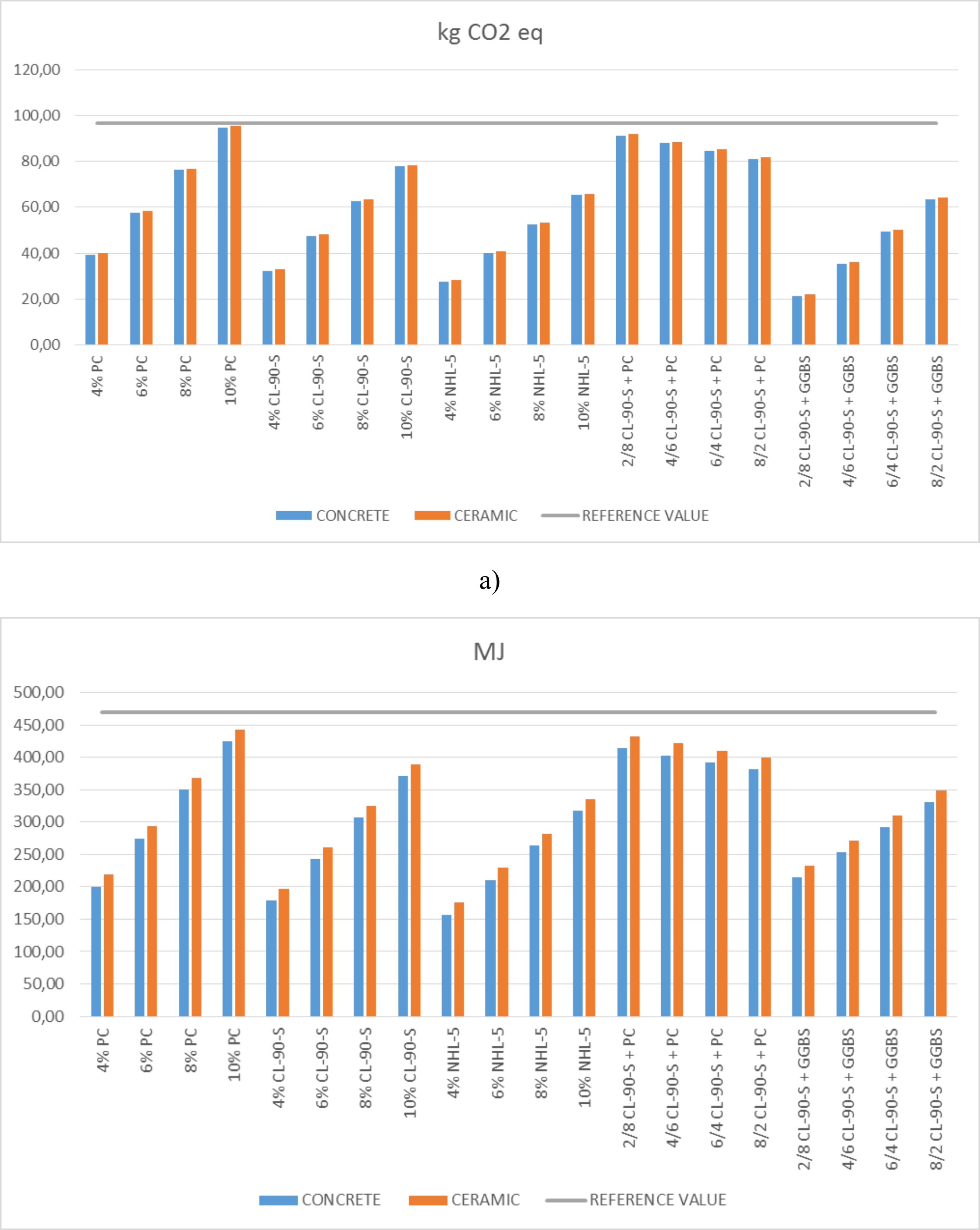


e)

FIGURE 7. Damages in specimens after the thawing/freezing test. a) Concrete based target with CL-90-S+GGBS 2/8 and b) Ceramic based target with NHL-5 10%

a) b)

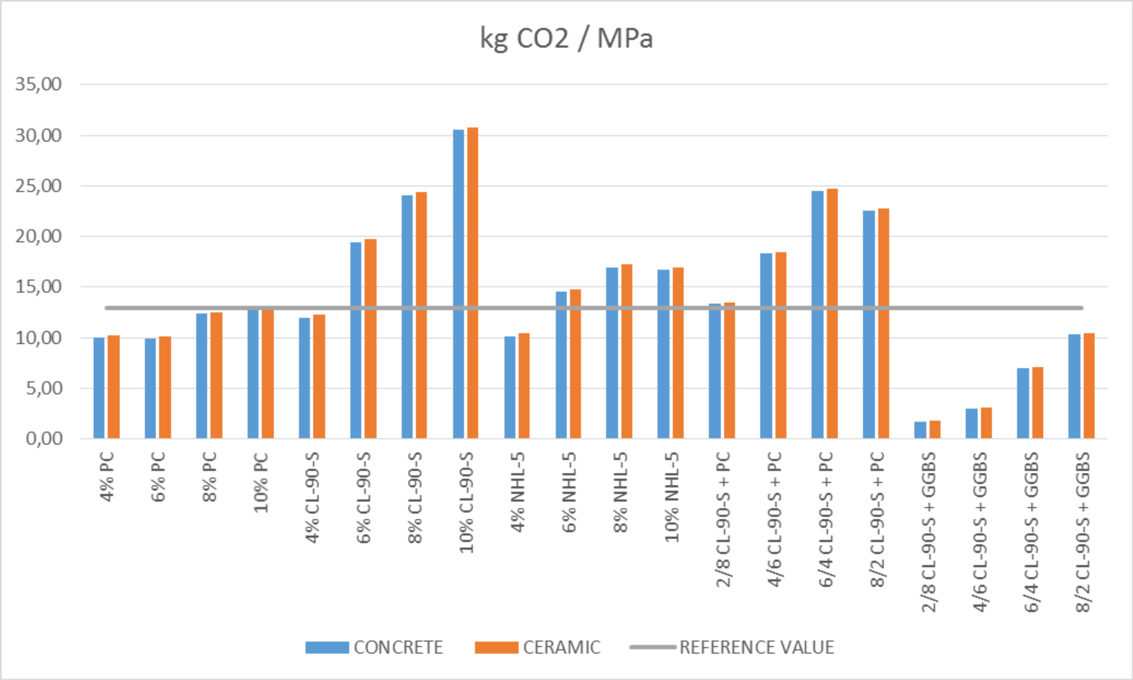
FIGURE 8. Environmental impact of the production of each unfired brick combinations based on a) Total embodied energy and b) Total CO_2 emissions.



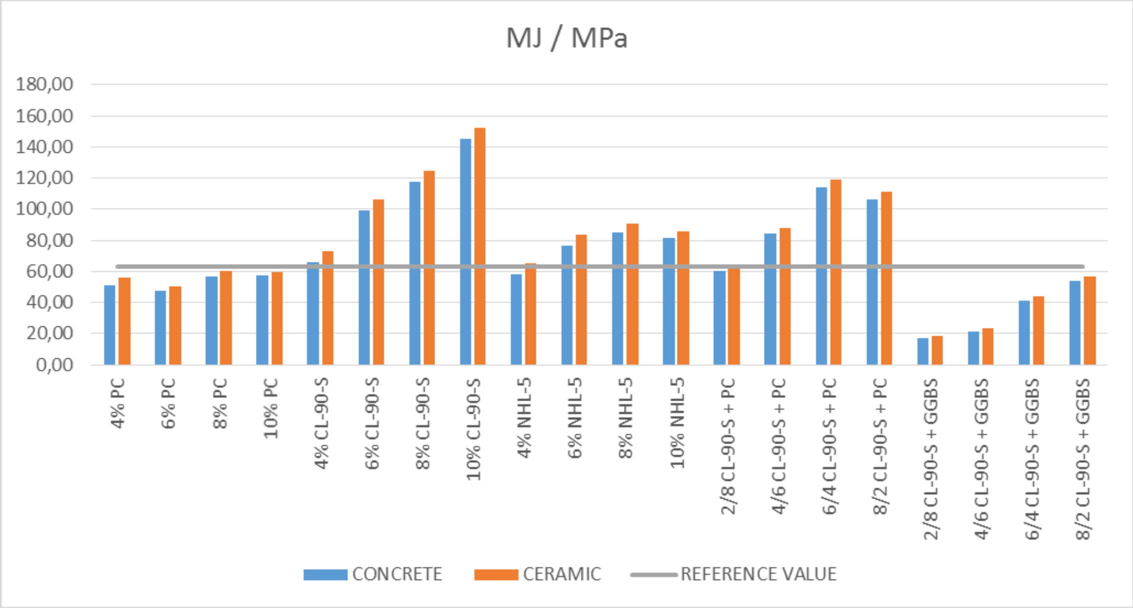
a)

b)

FIGURE 9. Environmental impact of the production of each unfired brick combinations based on a) Relative embodied energy and b) Relative CO_2 emissions.



a)



b)

TABLES

Table 1. Characterization of the marl soil, brick and concrete fine fractions.

FRX ANALYSIS			
OXIDES	CONCENTRATION (%)		
	MARL SOIL	BRICKS FINE FRACTION	CONCRETE FINE FRACTION

Na_2O	0.36	0.77	0.20
MgO	2.06	4.15	1.26
Al_2O_3	11.30	17.64	7.07
SiO_2	30.78	39.05	20.57
P_2O_5	0.12	0.18	0.13
SO_3	0.00	0.30	11.36
K_2O	1.96	3.56	0.92
CaO	36.64	17.10	42.23
TiO_2	0.53	0.64	0.36
Cr_2O_3	0.03	0.03	-
MnO	3.43	0.09	0.04
Fe_2O_3	0.01	5.98	2.47
Rb_2O	0.13	0.01	0.01
SrO	1.96	0.02	0.11
ZnO	-	0.013	0.02
ZrO_2	0.029	0.03	0.02
BaO	0.06	0.09	0.06
Cl	-	0.02	0.03
DRX MINERALOGY			
	MARL SOIL	BRICKS FINE FRACTION	CONCRETE FINE FRACTION
	Calcite	Quartz	Caolinite
	Illite	Calcite	Calcite
	Quartz	Muscovite	Quartz
	Caolinite	Dolomite	Gypsum
	Attapulgite	Clorite	Muscovite
	Ankerite	Gypsum	
Embodied CO2 (kg CO2/Tonne)	4	-	-
Embodied energy (MJ/Tonne)	100	-	-

TABLE 2. XRF obtained additives composition expressed as main oxides and embodied CO_2 and energy.

OXIDES (%)	CEM I	NHL-5	CL-90-S	GGBS
SiO_2	25	12	-	38
CaO	65	-	-	37
$Ca(OH)_2$	-	53	95	-
Fe_2O_3	0.5	-	-	0.5
Al_2O_3	3	10	-	12
SO_3	4	-	-	0.2
MgO	1	-	-	10
Embodied CO_2 (kg CO_2/Tonne)	930	635	760	52
Embodied energy (MJ/Tonne)	3,800	2,721	3,256	1,300

TABLE 3. Additives and binders based on their combinations and dosages tested.

COMBINATION	BINDER	PC (%)	CL-90-S (%)	NHL-5 (%)	GGBS (%)
1	PC	4	-	-	-
2		6	-	-	-
3		8	-	-	-
4		10	-	-	-
5	CL-90-S	-	4	-	-
6		-	6	-	-
7		-	8	-	-
8		-	10	-	-
9	NHL-5	-	-	4	-
10		-	-	6	-
11		-	-	8	-
12		-	-	10	-
13	CL-90-S+PC	8	2	-	-
14		6	4	-	-
15		4	6	-	-
16		2	8	-	-
17	CL-90-S+GGBS	-	2	-	8
18		-	4	-	6
19		-	6	-	4
20		-	8	-	2