Behavior of Mortar Samples with Waste Brick and Ceramic Under Freeze-Thaw Effect

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Abstract. Increasing number of industrial facilities and population concentration in particular regions along with overconsumption are main reasons of the increased environmental pollution. It is a necessity to preserve available resources and to keep the waste in control in order to achieve a sustainable development goal. In recent years, concepts of waste management, recycling and sustainability have gained importance with regards to the construction industry. Today, approximately 35 billion tons of concrete is produced worldwide and 80% of this amount consists of aggregated manufactured using natural resources. A significant environmental impact is the case even for the production of cement, a binding agent for concrete, which accounts for 1 ton CO_2 emission in order to produce 1 ton of cement. The main subject of this study is the production of a sustainable construction material with the use of ceramic instead of both aggregate and cement. Clay is defined as a common natural material with fine-grains, with layers and a high water absorption capacity. Ceramic products are construction materials which can replace cement generally in the form of artificial puzzolana. The main subject of this study is the use of the waste obtained from ceramic plants which produces ceramic products in mortars. Taguchi L9 array design was used as part of this experimental study. Water-binder ratio was set to 0.50 in the preparation of the mixes and natural aggregates were used. Aggregates were then replaced by pieces ceramic and brick at a percentage between 20 and 60% while cement was replaced by ceramic and brick powder at a percentage between 10 and 30%. The mixes were then subjected to freeze and thaw tests at 30, 60 and 90 cycles in accordance with ASTM C 666 standard. Dynamic modulus and mechanical properties of the mortars subjected to f-t effect were then identified. When the results of the tests were examined, it was found that the compressive strength at 7th and 28th days were decreased with the increase of the volume of ceramic and brick powder used while it was found that the use of ceramic and brick powder did not have a significant effect on the compressive strength at the 90th day. The use of ceramic and brick aggregate led to favorable results in terms of freeze-thaw resistance. Especially the use of 10% ceramic [(whiteware) CA] and 20% other ceramic [(brick) BA] aggregate in mortars subjected to 90 f-t cycles increased the dynamic modulus while similar results were found for the use of 5% ceramic powder and 10% brick powder in mortars subjected to 90 days of f-t cycles. This

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study shows that waste material obtained from ceramic and bricks industry can be repurposed in the construction industry.

Keywords: Sustainability · Waste management · Durability
Freeze-thaw resistance · Mortar

1 Introduction

Consumption of energy and natural resources has step up proportionately to civilization development and humanity population growth is one of the biggest environmental concerns today. In addition to the increasing emission of greenhouse effect gases, unbalanced consumption of natural resources will eventually lead to their exhaustion, as in the case of natural resources [1].

The exploitation of natural resources for construction purposes, in particular non-renewable resources, leads to millions of tons of construction and demolition waste (CDW) every year. Since most countries have no specific processing plan for these materials, they are sent to landfill instead of being reused and recycled in new construction. According to Eurostat, the total amount of waste generated in the European Union in 2010 was over 2.5 billion tones, of which almost 35% (860 million tons) derived from construction and demolition activities (Fig. 1). Of the total waste generated by the construction and demolition activities, and other activities, 97% was mineral waste or soils such as excavated earth, road construction waste, demolition waste, rock waste and others [2, 3].

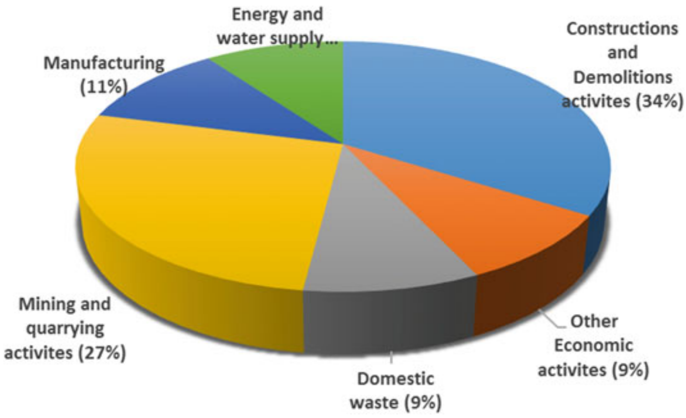

Fig. 1. Total waste generated in European Union [2]

This waste problem is becoming increasingly problem because of the growing quantity of waste (like industrial, construction and demolition) cause in spite of the measures which have been taken in recent years at European Union and Turkey, national and regional levels aimed at controlling and organizing waste management.

The necessity to manage these wastes is become one of the most urge upon issues of nowadays, requiring certain actions aimed at preventing waste generation like reuse, recycling and waste to energy systems. This necessity is promotion of resource recovery systems as a means of using the natural resources contained within waste and reducing environmental impact. Use of such waste, in addition to helping protect the environment, offers a series of advantages such as a reduction in the use of other raw materials, contributing to an economy of natural resources. Moreover, reuse also offers benefits in terms of energy, thus recovering the energy previously can be incorporated during production [4]. For instance, Portland cement clinker production consumes of energy that 850 kcal per kg of clinker and has a considerable environmental impact. This involves solid quarrying for raw materials, as it takes 1.7 tones to produce 1 tons of clinker, as well as the emission of greenhouse and other gases (NOx, SO_2, CO_2) into the atmosphere. Around 850 kg of CO_2 are spread per tons of clinker produced [5]. In this way, both the lost energy is recovered and pollution is prevented.

As many developing countries have all over the world, Turkey has also been generating a huge amount of CDW waste, which generates serious environmental problems to deal with. Because of the Urban Renewal Law at Turkey, it is estimated that demolition and maintenance of the structures at the end of their economic span result 4–5 million ton/year of concrete and demolish waste (CDW). As recycling and reuse are alternatives to minimize the impact of energy and raw material consumption on the environment, waste that can be potentially used for concrete production can be recycled aggregate, which obtained via concrete and demolish waste (CDW) [6].

Concrete is the most common and useful material, which has contributed to the progress of civilizations throughout last century, in the construction industry. However, construction activities demand a significant amount of natural materials, which significantly modifies the natural sources and creates environmental problems, in order to produce cement and aggregate [6, 7]. The increasing and unsustainable consumption of natural resources is the cause of great concern for the environment and economy with the excessive production of construction and demolition waste (CDW). Construction industry is a big sector, which can include several efforts to promote ecological efficiency. Thanks to this feature, waste can be considered that the reusable of CDW at new construction [8]. In other words, construction and demolition waste (CDW) can be use for possible feasible alternative as aggregates [as named recycled aggregates (RA)] into the production of new concrete, mortar or plaster. Recycled aggregate has become one of the sustainable technologies in concrete industry because of great environmental advantages in past decades [9–11]. Reuse of construction and demolition wastes (CDW) may be provide a beneficial way which leads sustainable engineering approaches to mortar and concrete mix design [6, 7]. In other words, we can say that fine or coarse aggregates and cement could be successfully replaced by different kind of solid waste. This waste was mainly composed of concrete and masonry waste, both components with a high potential for being re-used or recycled as unbound materials or cement-treated materials in road construction, recycled aggregates (RA) for the production of concrete, mortar, drainage materials and also for asphalt materials [12].

When investigations involving recycled aggregates (RA) and supplementary cementing materials are analyzed, aggregates with pozzolanic properties are generally seen to be used more frequently as recycled aggregates (RA) or supplementary cementing materials such as blast furnace slag, pulverized soda lime glass, residuals of glass separate collection, treated bottom ashes and biomass fly ash, activated slag, rice husk ash, metakaolin and calcined clays, ceramic residues [13] for cement and concrete, bricks, tile, wood, etc. for aggregate.

Pozzolan is defined as a siliceous material which, in itself, possesses little or no cementing property but which will, in finely divided form and in the presence of moisture react chemically with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties [14]. Pozzolans and other materials with similar characteristics, when used in mortars or concrete, allow reducing the cement content for a pre-determined mechanical strength, thus replacing a material with very high-energy consumption in its manufacture [8].

Ceramic material, which is defined as an inorganic, non-metallic, generally crystalline oxide, nitrile or carbide material, can withstand very high temperatures and raw materials include clay minerals such as kaolinit [15]. Heat treated clays from ceramic products, such as bricks and tiles that were milled and incorporated in mortar, was used materials in ancient times, when natural pozzolans were not available [16, 17].

Researchers is revealed that ceramics (Fig. 2) might have potential as pozzolans or as aggregates when incorporated into mortars or concrete along with being compatible with buildings masonry. Apart from these environmental advantages, there are other benefits from using ceramic waste. When used to partially replace the constituents of mortars, ceramic particles help to reduce the consumption of natural aggregates or binder [17].

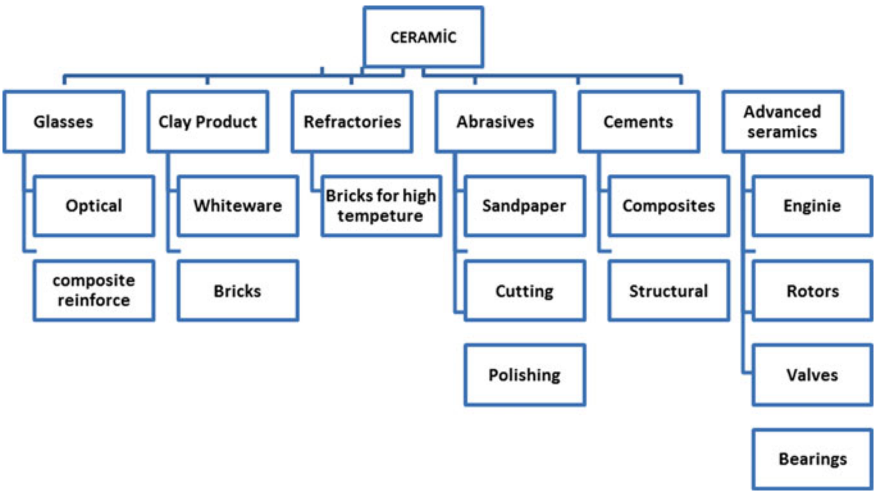

Fig. 2. Classification of ceramic by type [19]

Ceramic waste may originate from two sources, which is the ceramics industry and is associated with construction and demolition. It has been estimated that about 30% of the daily production in the ceramic industry goes to waste. Most of the previous studies have investigated the use of ceramic waste in concrete or mortar as sand or coarse aggregate. Some researches were also done in which the use of the materials in concrete as a substitute for cement were investigated [4, 18].

Various authors have researched the possible use of ceramic waste. Most of these studies do not include ceramic waste from CDW, but rather from ceramic industry waste: clay roof tiles, ceramic sanitary ware and brick. Finely crushed ceramic waste has been used for making cement, as a substitute of cement for mortar production [20] and as an addition to mortar. The coarse fraction of ceramic waste has been used as recycled aggregate in concrete production and fine fraction as recycled sand in mortars [12].

Ceramic powder and grains (Fig. 3) have been widely used in mortars. The variety of these materials was observed that when they were combined with certain substances the resulting mortars have improved characteristics. Over time, it has been demonstrated that the addition of small ceramic particles confers improved characteristics on mortars and that pozzolanic reactions might occur [16].

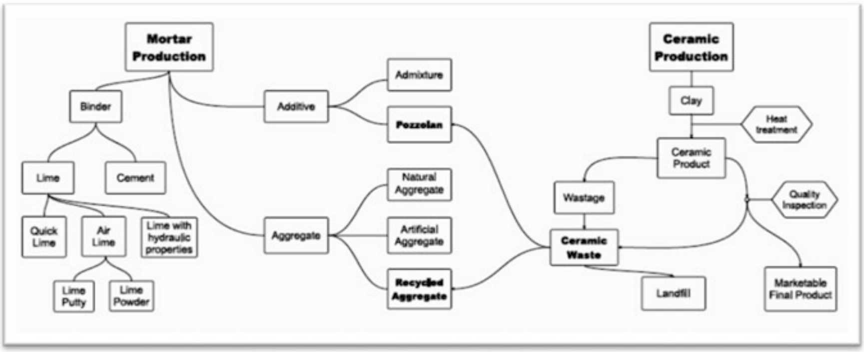

Fig. 3. Type of aggregate used in this study [17]

During the freeze-thaw cycles, the concrete or mortar will expand and contract alternately caused by conversion between solid state and liquid state of water in the microstructure. These expansion and contraction of the water can fatigue the concrete microstructure over time and may lead to the disintegration and failure of the concrete material. And then concrete or mortar will be caused after the action of freeze-thaw cycles [21].

In this study, the recycling rate of baked earth products obtained from brick and ceramic industry was increased with their use in mortar production. In this context, this study used 20–60% ceramic products instead of natural aggregate and 10–30% ceramic products instead of cement. Some of the waste ceramic materials were used into mortars mixtures in different proportions, partially replacing the natural sand or binder at, is to determine the influence of ceramic aggregate and ceramic powder on the properties and freeze-thaw resistance of cement mortar.

2 Materials and Method

2.1 Materials

In the mortar production process, washed stream aggregate at 0–4.75 mm sieve size obtained from the city of Kastamonu was used. Ceramic waste (brick and ceramic aggregate) was used in combination with the aggregate replacing the natural aggregate at a ratio between 20 and 60%. The particle distribution of waste aggregate was then reduced to 0–4.75 mm in order for it to match natural aggregate size. CEM I 42.5 R cement was used in mortar production in accordance with TS EN 197-1 standard. Ceramic waste (CA and BA powder) was used in combination with cement replacing the cement at a ratio between 10 and 30%. Chemical and physical properties of the binding agents used in mortar production are shown in Table 1.

Table 1. Chemical and physical properties of the binding agents

Component (%)	CEM I 42.5 R	Ceramic powder	Brick powder
CaO	64.70	1.73	8.81
SiO_2	19.12	55.73	54.20
Al_2O_3	4.75	29.76	14.90
Fe_2O_3	3.53	5.41	5.75
MgO	0.94	3.30	6.56
Na_2O	0.21	1.96	2.03
K_2O	0.88	3.11	2.22
SO_3	2.85	0.29	0.59
Cl^-	0.009	–	
Free lime	1.41	–	
Loss on Ign.	2.36	6.89	
Insolubles	0.23		
C_3S	58.79		
C_2S	12.69		
C_3A	7.74		
C_4AF	9.83		
Specific W.	3.13	2.55	2.95
Specific surface (cm^2/g)	3400	3520	3330

Granulometric properties of the aggregate used in mortar production are shown in Fig. 4. Physical properties of the aggregates are shown in Table 2.

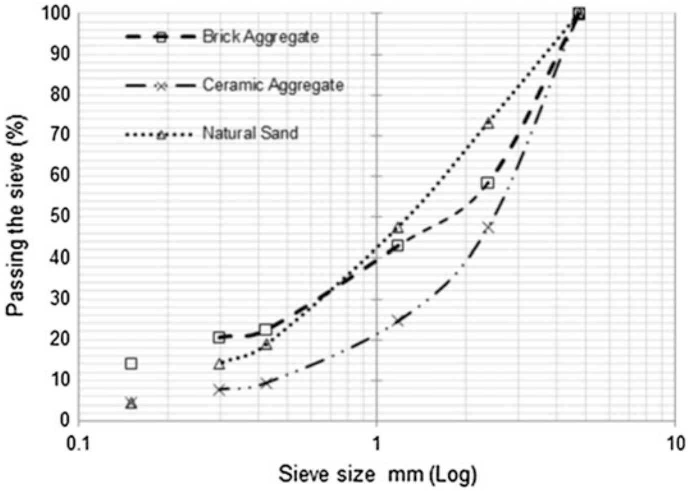

Fig. 4. Granulometric properties of aggregates

Table 2. Physical properties of aggregates

	Brick aggregate	Ceramic aggregate	Natural aggregate
Specific weight (SSD)	2.52	2.40	2.63
Water absorption (%)	4.6	8.3	2.3

2.2 Method

In this study, ceramic (CA) and brick(BA) powder was used in combination with the cement replacing the cement at the ratios of 5, 10 and 15%. Ceramic powder was obtained grounding the ceramic waste for 120 min using a ball mill. Due to the fact that the material has the slope of the cement, Due to the fact that the material, which is the factory waste, has the slope of the cement (Table 1), no grounding process was necessary for brick powder. Ceramic and brick aggregate was used in combination with the natural aggregate replacing the natural aggregate at the ratios of 5, 10 and 15%. Ceramic and brick waste was reduced to a fine-grain aggregate size using a rock crusher. Taguchi L9 assay matrix was used in the preparation of mixs. The variables used in the experimental study are given in Table 3.

Table 3. Dependent variables of Taguchi L9 assay matrix

Taguchi L9 assay matrix		Level 1 (%)	Level 2 (%)	Level 3 (%)
Aggregate replacement	Ceramic aggregate	10	20	30
	Brick aggregate	10	20	30
Cement replacement	Ceramic powder	5	10	15
	Brick powder	5	10	15

10 different mix, 9 with aggregate and cement replacements and 1 reference, were prepared as part of mortar preparation process. Mix ratios of the mortars are given in Table 4.

Table 4. Aggregate and cement replacement ratios

Mix #	Aggregate replacement		Cement replacement	
	Ceramic aggregate (%)	Brick aggregate (%)	Ceramic powder (%)	Brick powder (%)
1	10	10	5	5
2	10	20	10	10
3	10	30	15	15
4	20	10	10	15
5	20	20	15	5
6	20	30	5	10
7	30	10	15	10
8	30	20	5	15
9	30	30	10	5
10 (R)	0	0	0	0

W/B (water/binder) ratio of the mortar mix was set at 0.50 while their a/c (aggregate/cement) ratio was set at 3. Mortars were produced in prismatic samples of $4 \times 4 \times 16$ cm in size. Mortars were removed from the mold after 24 h and preserved in water saturated with lime at 20 ± 2 °C until the experiment day. Uniaxial compression tests and 3-point flexural tests were conducted on the mortar samples at 7th, 28th and 90th day. Freeze-thaw resistance of the mortars produced using ceramic products was explored in order to determine their durability properties. Having been cured in drinking water for 28 days, the mortar samples were then subjected to f-t tests.

Once the curing process was completed, mortars were subjected to freeze-thaw tests at 30, 60 and 90 cycles. Freeze-thaw temperatures and durations were defined in accordance with the ASTM C 666 standard in the f-t tests. Durability factors of the mortars were identified having measured their relative dynamic elasticity modulus. Relative dynamic modulus was calculated using Eq. (1). Durability factor, on the other hand, was calculated using Eq. (2).

$$P_c = \frac{n_c^2}{n^2} \times 100 \tag{1}$$

where c is the number of cycles of freezing and thawing, nc is the resonant frequency after c cycles, and n is the initial resonant frequency (at zero cycles).

$$DF = \frac{N}{M} \times P_c \tag{2}$$

where Pc is the relative dynamic modulus, N is the number of cycles completed, and M is the planned duration of testing. Testing is usually halted when the relative dynamic modulus falls below 50–60% of its initial value.

3 Results and Discussion

3.1 Mechanical Properties of Mortars

Compressive strengths of the mortars at 7th, 28th and 90th days were calculated relatively. The effect of replacement ceramic aggregate ratio on compressive strength is shown in Fig. 5.

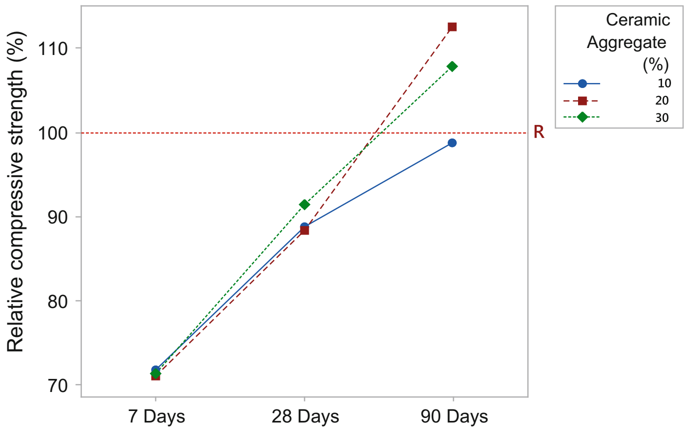

Fig. 5. The effect of replacement ceramic aggregate ratio on relative compressive strength

As shown in Fig. 5, increasing the curing time increases compressive strength. The compressive strength results obtained from the 7th day and 28th day shows that the use of ceramic aggregate decreases the compressive strength by approximately 10–30%. When the compressive strength results obtained from the 90th day are examined, it was found that the use of ceramic aggregate at ratios of 20 and 30% increases the compressive strength by approximately 10%. This situation can be explained that the material under passing the sieve, which is kept under 25% sieve, was showed a puzolonic feature and increased its strength. The use of 10% ceramic aggregate has an unfavorable effect on the compressive strength at the 90th day. The use of 30% ceramic aggregate has a favorable effect on the compressive strength at the 28th day. However, considering the compressive strength results for 90th day, it can be said that the use of 20% ceramic aggregate is more suitable. The effect of replacement brick aggregate ratio on compressive strength is shown in Fig. 6.

As shown in Fig. 6, increasing the curing time increases compressive strength of the mortars with brick aggregate additive. The use of brick aggregates at the ratios of 20 and 30% gave similar results for all experiment days. Compressive strength of the

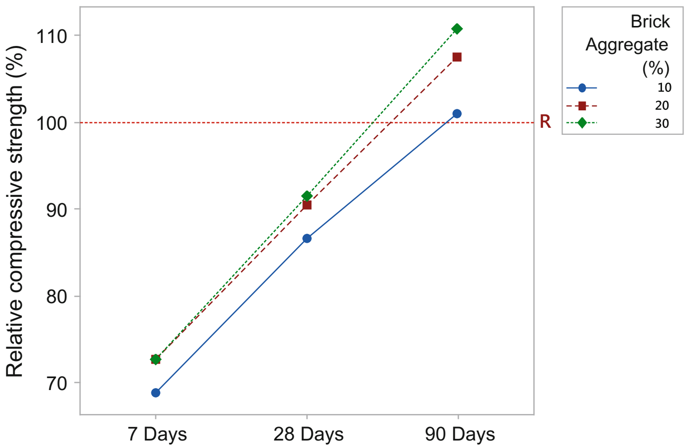

Fig. 6. The effect of replacement brick aggregate ratio on relative compressive strength

mortars at the 28th day is reduced by 10–15% when compared to the reference mix. However, Fig. 6 shows the favorable effects of the use of brick aggregate at the 90th day. The use of brick aggregate, especially at a ratio between 20 and 30%, increases the compressive strength by approximately 10%. As it was the case for ceramic aggregate, the use of 10% brick aggregate is not suitable enough. The effect of replacement ceramic powder ratio on compressive strength is shown in Fig. 7.

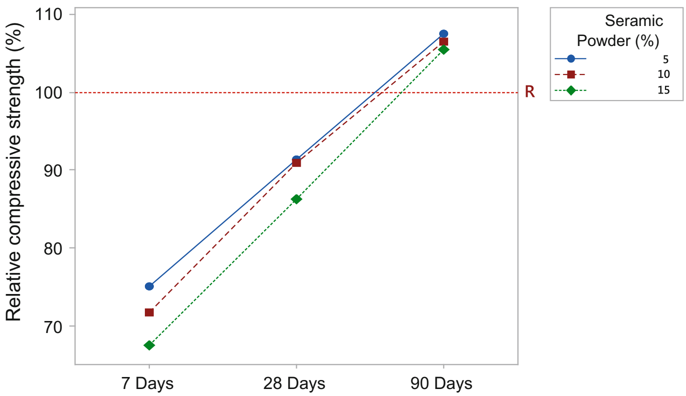

Fig. 7. The effect of replacement ceramic powder ratio on relative compressive strength

In terms of compressive strength at the 7th day, increasing the ceramic powder ratio leads to decreases in the compressive strength. The use of ceramic powder at a ratio between 5 and 10% decreases the compressive strength by approximately 10% at the 28th day. Exploring the compressive strength at the 90th day, a distinctive difference was found between mortars. The use of ceramic powder increases the compressive strength by approximately 5% at the 90th day. The effect of replacement brick powder ratio on compressive strength is shown in Fig. 8.

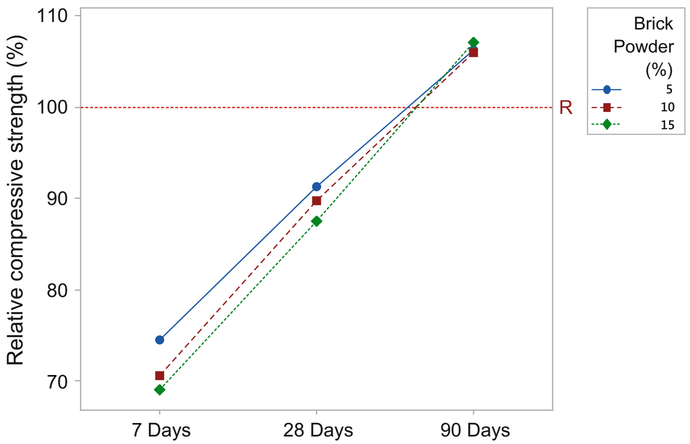

Fig. 8. The effect of replacement brick powder ratio on relative compressive strength

As shown in Fig. 8, increasing the brick powder ratio has an unfavorable effect on the compressive strength at 7th and 28th days. However, this unfavorable effect is eliminated at the 90th day. The use of brick powder increases the compressive strength by approximately 5% at the 90th day, as it was the case for ceramic powder.

3.2 Freeze-Thaw Resistance Properties of the Mortars

Properties such as relative dynamic modulus (Eq. 1) and durability factor (Eq. 2) were identified for the freeze-thaw resistance of the mortars. Figure 9 shows the relative dynamic modulus of the mortars. The graph in Table 4 shows the mixs with their relevant numbers and their mix properties. Mix #10 represents the reference mortar. Increasing the f-t cycles in the freeze-thaw tests applied to the mortars decreases the relative dynamic modulus. The optimal mix ratios were defined with Taguchi optimization conducted on the f-t tests with 30, 60 and 90 cycles. Table 5 shows the optimized and estimated values for relative dynamic modulus calculated using maximized function.

Durability factors of the mortars are shown in Fig. 10 with respect to their mix numbers. It was found that mortars show similar properties at the end of 30 and 60 cycles. However, mortars show distinct differences in terms of their durability factors at the end of 90 cycles. An optimization was made using the maximized function for the durability factors of mortars. Optimization results are shown in Table 6.

The optimization conducted on the relative dynamic modulus and durability factors showed that the optimal ceramic aggregate ratio is between 10 and 20% while the optimized brick aggregate ratio is between 20 and 30%. It was found that a ceramic

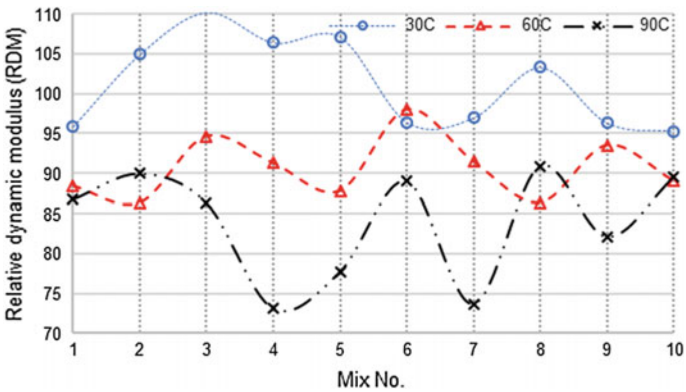

Fig. 9. Relative dynamic modulus of mortars

Table 5. Optimization results for the relative dynamic modulus

Cycle	Ceramic aggregate (%)	Brick aggregate (%)	Ceramic powder (%)	Brick powder (%)	Estimated RDM
30C	10	20	15	15	114.4
60C	20	30	15	10	98.4
90C	10	20	5	10	97.2

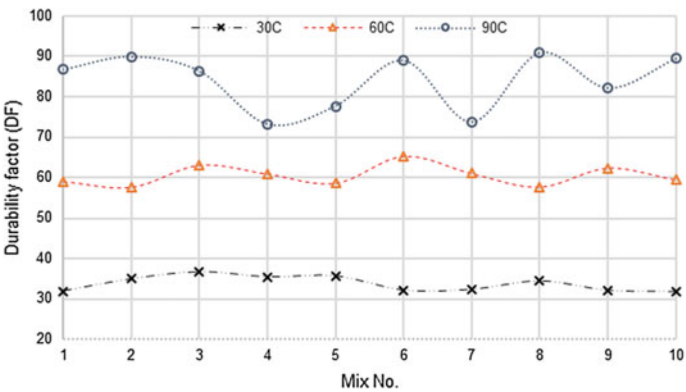

Fig. 10. Durability factors of mortars

Table 6. Optimization results for durability factor

Cycle	Ceramic aggregate (%)	Brick aggregate (%)	Ceramic powder (%)	Brick powder (%)	Estimated RDF
30C	10	20	15	15	38.2
60C	20	30	15	10	65.6
90C	10	20	5	10	97.2

powder ratio of 5 or 15% and a brick powder ratio between 10 and 15% contribute to the freeze-thaw strength.

4 Conclusions

The following conclusions can be drawn from this experimental study;

- The use of ceramic aggregate at ratios of 20 and 30% increases compressive strength.
- The use of brick aggregate at ratios of 20 and 30% has a favorable impact on the compressive strength.
- The use of brick and ceramic aggregate at a ratio of 10% has an unfavorable impact on the compressive strength.
- Increasing the amount of ceramic and brick powder used results in an unfavorable effect on compressive strength at 7th day and 28th day. However, this unfavorable effect is eliminated at the 90th day due to pozzolanic activity.
- The use of ceramic and brick aggregate led to favorable results in terms of freeze-thaw resistance. Especially the use of 10% ceramic and 20% brick aggregate increased the relative dynamic modulus of mortars subjected to 90 f-t cycles.
- The use of ceramic and brick powder improves freeze-thaw resistance of the mortars. The use of 5% ceramic and 10% brick powder increased the relative dynamic modulus of mortars subjected to 90 f-t cycles.
- This study shows that waste material obtained from ceramic and bricks industry can be repurposed in the construction industry. It will be possible to produce sustainable construction materials as a result of utilization of such waste material.
- The use of industrial waste which leads to environmental problems in the construction industry is important in terms of ecology, sustainability, durability and recycling.

References

1. Alves AV, Vieira TF, Brito J, Correia JR (2014) Mechanical properties of structural concrete with fine recycled ceramic aggregates. Constr Build Mater 64:103–113
2. Silva RV, Brito J, Dhir RK (2014) Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. Constr Build Mater 65:201–217

3. Silva RV, Brito J, Dhir RK (2015) Comparative analysis of existing prediction models on the creep behaviour of recycled aggregate concrete. Eng Struct 100:31–42
4. Khalil NM (2014) Exploitation of the ceramic wastes for the extraction of nano aluminum oxide powder. J Ind Eng Chem 20:3663–3666
5. Puertas F, García-Día I, Barba A, Gazulla MF, Palacios M, Gómez MP, Martínez-Ramírez S (2008) Ceramic wastes as alternative raw materials for Portland cement clinker production. Cement Concr Compos 30(9):798–805
6. Çakır Ö (2014) Experimental analysis of properties of recycled coarse aggregate (RCA) concrete with mineral additives. Constr Build Mater 68:17–25
7. Pacheco-Torgal F, Jalali S (2010) Reusing ceramic wastes in concrete. Constr Build Mater 24(5):832–838
8. Silva J, Brito J, Veiga R (2008) Fine ceramics replacing cement in mortars partial replacement of cement with fine ceramics in rendering mortars. Mater Struct 41:1333–1344
9. Ann KY, Moon HY, Kim YB, Ryou J (2008) Durability of recycled aggregate concrete using pozzolanic materials. Waste Manag 28:993–999
10. Khaldoum RK (2007) Mechanical properties of concrete with recycled coarse aggregate. Build Environ 42(1):407–415
11. Mueller A, Sokolova SN, Vereshagin VI (2008) Characteristics of lightweight aggregates from primary and recycled raw materials. Constr Build Mater 22(4):703–712
12. Ledesma EF, Jimenez JR, Ayuso J, Fernandez JM, Brito J (2015) Maximum feasible use of recycled sand from construction and demolition waste for eco-mortar production e Part-I: ceramic masonry waste. J Clean Prod 87:692–706
13. Bignozzi MC, Saccani A (2012) Ceramic waste as aggregate and supplementary cementing material: a combined action to contrast alkali silica reaction (ASR)
14. Mehta PK (1987) Natural pozzolans: supplementary cementing materials in concrete. CANMET Spec Publ 86:1–33
15. Carter CB, Norton MG (2007) Ceramic materials: science and engineering. Springer, Berlin, pp 3–4. ISBN: 978-0-387-46271-4
16. Matias G, Faria P, Torres I (2014) Lime mortars with ceramic wastes: characterization of components and their influence on the mechanical behaviour. Constr Build Mater 73:523–534
17. Matias G, Faria P, Torres I (2014) Lime mortars with heat treated clays and ceramic waste: a review. Constr Build Mater 73:125–136
18. Andrejkovicova S, Velosa AL, Ferraz E, Rocha F (2014) Influence of clay minerals addition on mechanical properties of air lime–metakaolin mortars. Constr Build Mater 65:132–139
19. Materials and Manufactoring processes 20 (2017) http://slideplayer.com/slide/4616756/
20. Naceri A, Hamina M (2009) Use of waste brick as partial replacement of cement in mortar. Waste Manag 29:2378–2384
21. Shang H, Zhao T, Cao W (2015) Bond behavior between steel bar and recycled aggregate concrete after freeze-thaw cycles. Cold Reg Sci Technol 118:38–44