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Design of the usability of ceramic sanitary ware waste in cement production using the Taguchi method

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Abstract: The cement process is one of the industries where energy is consumed intensively. High levels the amount of carbon dioxide emission reaches since the nature of the raw materials used in its production. At this point, using industrial wastes and by-products containing oxides such as calcium, silica, alumina, and iron oxides blended cement reduces energy consumption and carbon dioxide emissions. In this study, the effects of using ceramic sanitary ware waste (CSW) instead of clinker on the cement grinding stage were investigated. The grinding tests were carried out with clinker in a ball mill, according to grinding parameters as ball filling ratio, ball diameter, and grinding time by using Taguchi method for optimization of cement grinding condition. The reference and blended cements with CSW were determined compressive strength.

Keywords: cement, ceramic waste, Taguchi method

1. Introduction

Nowadays, higher energy demand, depletion natural resources, and environmental pollution are still one of the most important issues of humanity, due to population growth and increased in the life level of the society in parallel with technological developments, industrialization, and urbanization. Energy-related CO_2 emissions in the world reached 31.5 Gt in 2020, when it was 23.1 Gt in 2000. In Turkiye, this value increased to 383 million tons in 2019 from 275 million tons in 2013 (BP,2020).

The cement industry is one of the leading sectors in the world where energy is consumed intensively and emits the most CO_2 due to the nature of its process and raw materials. In 2018, process-induced industrial CO_2 emissions in the world were 8.5 Gt. Here, the highest emission was from the cement sector with 2.3 Gt (IEA, 2021).

Cement, which has been produced from the most common materials in the world since ancient times, will maintain its importance in the future, with its flexibility of use properties, long-term durability, and cost advantage. For this reason, numerous technological studies are carried out in order to reduce the damage caused by cement to the environment both in the production and usage phases. (Jos, 2014).

Millions of tons of industrial waste containing mineral additives are produced annually worldwide. Pollution of these wastes in air, soil, and water, and storage problems that bring great costs to both the industry and the society constitute a major problem. Using them as cement additives, the environmental risk they cause, will be reduced and storage problems will be alleviated. In addition, an economically beneficial cycle will be provided, as they are recovered for production (TOBB, 2014).

Ouyang et al. (2022) studied the understanding of the mechanisms of the influence of ceramic waste powder on the properties (i.e., rheology, hydration, and strength) of cement-based materials. To further clarify the influence of ceramic waste powder, the surface characteristics of ceramic waste powder can be explored by the Zeta potential test. Scanning electron microscopy was used to investigate the morphology of hydrates on the surface of ceramic waste powder, quartz powder, and Portland cement (PC) particles during the early stages of hydration. The effect of ceramic waste powder on the hydrates at a late curing age was studied by X-ray diffraction and thermogravimetric analysis. At the same time, the rheological properties of cement paste containing 30% ceramic waste powder and pure cement paste

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were compared. Finally, the effects of ceramic waste powder on the development of strength of cementitious materials were confirmed by analysing the crack propagation of hardened cement paste containing ceramic waste powder as well as the fracture surface between ceramic waste powder and hydrates.

Pacheco-Torgal and Jalali (2010) examined the feasibility of using ceramic wastes in concrete in terms of strength and durability. According to the results, concrete with 20% cement replacement, although it has a minor strength loss possess increase durability performance because of its pozzolanic properties. Results also show that concrete mixtures with ceramic aggregates perform better than the control concrete mixtures concerning compressive strength, capillary water absorption, oxygen permeability, and chloride diffusion thus leading to more durable concrete structures.

Pitarch et al. (2021) investigated the pozzolanic activity of three different types of ceramic waste (red clay bricks, ceramic tiles, and ceramic sanitary ware) to provide further information on ceramic waste/Portland cement blended binders. The results show that these three different ceramic waste types are potential candidates for up to 25 wt% to replace PC.

While Wang et al. (2019) investigated the effect of ceramic polishing powder on the nucleation and growth of hydrates in cement paste, Awoyera et al. (2016) investigated the mechanical characterization of concrete made using ceramic floor and wall tile wastes from construction and demolition areas as partial substitutes for natural aggregates.

All these studies have successfully proved the viability of employing ceramic as pozzolanic admixtures in PC systems and have consequently encouraged the use of blended cements with lower clinker contents (Ay and Unal, 2000; Puertas et al., 2006; Sanchez de Rojas et al., 2006; Filho et al., 2007; Pereira-De-Oliveira et al., 2012; Mas et al., 2016). The purpose of this research is to investigate the use of ceramic sanitary ware wastes instead of clinker in the cement grinding process.

2. Materials and methods

2.1. Material

Table 1 shows the chemical compositions of clinker (C), gypsum (G), and CSW tested by XRF. CSW was obtained from the waste site of the cement factory where laboratory studies were conducted. Helium pycnometer was used for specific gravity determination. Specific gravity values were 3.24, 2.35 and 2.60 g/cm^3 for C, G, and CSW, respectively.

Table 1. Chemical composition of C, G, and CSW ceramic wastes (% by mass)

Components	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Other	LOI
C	20.61	4.95	3.79	67.04	1.49	0.63	0.04	0.73	0.42	0.30
G	1.45	0.54	0.25	34.27	0.30	40.83	0.03	0.11	0.01	22.21
CSW	67.05	22.29	0.98	2.86	0.48	0.34	3.27	0.88	0.68	1.17

2.2. Method

A ball mill with a diameter of 40 cm, a length of 52 cm, and 50 revolutions per minute was used in the grinding experiments. Within the scope of the study, the grinding kinetics of clinker was investigated by filling the ball mill with balls in 3 different ratios (26%, 30% and 34%) and 3 different size ranges (fine, medium and coarse) (Table 2).

Ball diameter, grinding time, and ball filling ratio were chosen as independent grinding parameters. The effects of these parameters on grinding were investigated using the Taguchi Experimental Design technique for the optimization of clinker grinding. The optimum grinding condition of the clinker was determined using the Minitab program.

The experimental design is a method that proposes to perform tests to find the optimal levels of variables affecting the product. Finding all possible effects of all variables at once would require many trials. To reduce this large number of trials, the Japanese scientist Genichi Taguchi has developed standard tables, which he called the "Taguchi Method", consisting of orthogonal arrays, which contain fewer trials but can reveal all the effects of the factors (Taguchi, 1987; Tra Lam, 2023). These tables, called

Taguchi orthogonal sequences, are depicted with symbols such as L4, L9, L16, and L32. The numbers show the number of experiments in the table. According to Taguchi, if the aim is to reach the minimum value in a process, the performance statistics formula in equation 1 is used to determine the optimum levels of the parameters (Turkmen, 2003; Ozbay, 2009). If the goal is to reach the minimum in a process, the parameter levels that maximize S/N are optimum. (Akcicek, 2007, Montgomery, 1991).

Table 2. Mill charge consisting of fine, medium, and coarse balls

Ball diameter (mm)	**Fine ball weighted (%)**	**Medium ball weighted (%)**	**Coarse ball weighted (%)**
40	-	12.5	35.0
30	15.0	25.0	30.0
25	20.0	25.0	20.0
20	30.0	25.0	15.0
15	35.0	12.5	-
Total	100.0	100.0	100.0

$$S/_{N} = -10\log\left(\frac{1}{n}\sum_{n=1}^{n} y^2\right) \quad (1)$$

where S/N is signal to noise ratio, n is number of repeated experiments and y is d_{80} grain size.

3. Results and discussion

In order to find the optimum grinding conditions for clinker, experiments were designed with 3 variable parameters and variable levels (Table 3).

Table 3. The independent variables and levels used for clinker grinding optimization.

Variable parameters	**Variable levels**		
	Low	**Medium**	**High**
Ball fill ratio (%)	0.26	0.30	0.34
Ball diameter (mm)	Fine ball weighted	Medium ball weighted	Coarse ball weighted
Grinding time (minute)	40	50	60

For these variable parameters and levels, it was sufficient to perform 9 experiments according to the L9 (33) arrangement of Taguchi orthogonal sequences. For the grinding tests, according to the L9 design, fine, medium, and coarse-sized balls were placed in the mill with 26%, 30%, and 34% ball filling ratios, and then clinker was fed into the mill according to each filling ratio. Samples were taken from the ball mill every 10 minutes, and the clinker's specific surface area (Blaine) and the particle size distribution analysis of the obtained product were made (Table 4). When the experimental results were examined, the finest grinding product was obtained in the C1 sample, and the coarsest grinding product was obtained in the C7 sample.

The calculations were made by using Taguchi method with the Minitab program. The method gave the optimum levels of the parameters that maximize S/N ratios are optimum. The optimum grinding condition for clinker was 60 minutes of grinding at a 26% fill rate and consisting of balls in the fine-size ball weight group as seen from Figure 1.

In the next stage of the work, experimental tests were made and CSW was used as a substitute material to reduce clinker in cement production. Table 5 gives material ratios used in the production reference cement (R) and blended cements with CSW. Samples of blended cements include CSW which were coded SW as shown in Table 5. R is a Portland cement obtained by grinding only clinker and gypsum, which does not use any waste.

Table 4. L9(33) design and experimental results for clinker grinding tests

	Ball fill ratio (%)	Ball diameter (mm)	Grinding time (minute)	Blaine (g/cm^2)	d_{80} (µm)
C1	0.26	Fine	40	5,370	13.91
C2	0.30	Fine	50	4,591	22.99
C3	0.34	Fine	60	4,743	26.94
C4	0.30	Medium	60	4,444	26.72
C5	0.34	Medium	40	4,119	34.94
C6	0.26	Medium	50	4,931	15.00
C7	0.34	Coarse	50	3,825	39.21
C8	0.26	Coarse	60	4,774	26.49
C9	0.30	Coarse	40	4,693	30.20

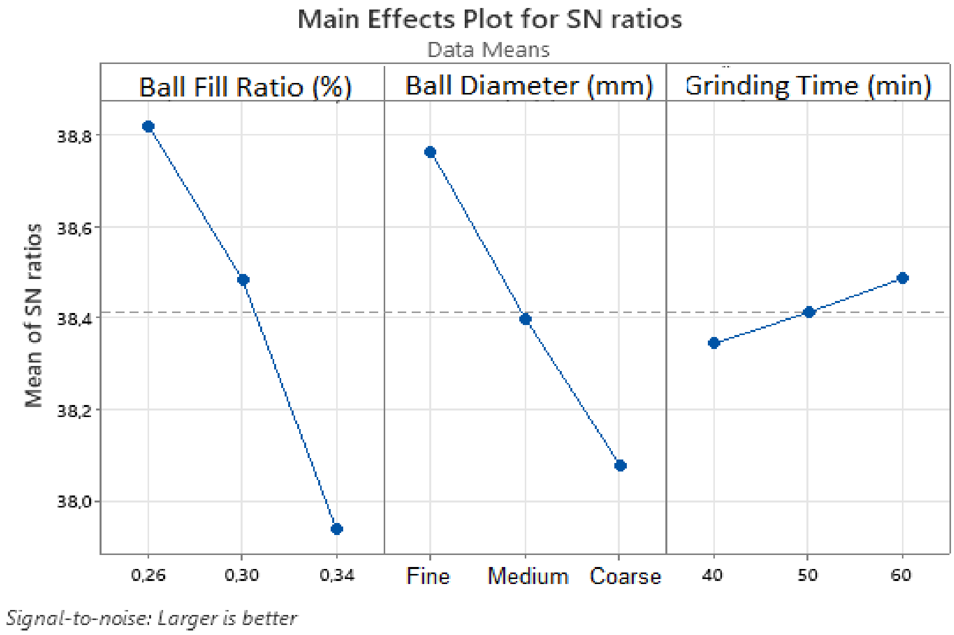

Fig. 1. S/N analysis result according to the Taguchi method

Table 5. Material ratios used in the production of reference and blended cements

Sample	C	G	CSW
R	96	4	-
SW2	94	4	2
SW4	92	4	4
SW6	90	4	6
SW8	88	4	8
SW10	86	4	10
SW12	84	4	12
SW14	82	4	14
SW16	80	4	16
SW18	78	4	18

These 10 cement samples shown in Table 5 were obtained by grinding in the ball mill according to specified optimum conditions by Taguchi method. 2-, 7-, and 28-days compressive strength of the cement samples were determined considering to TS EN 196-1 'Cement test methods - Part 1 - Determination of Strength' standard.

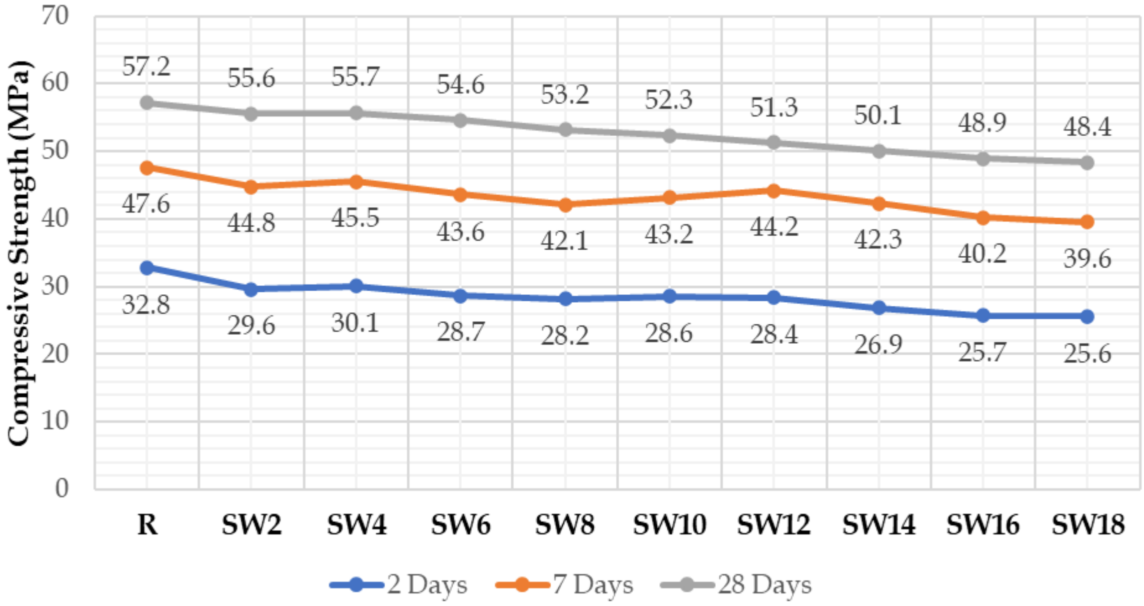

Fig. 2. Compressive strength of reference cement and cements with CSW additives

When the compressive strength values are examined, the cement's (CSW-ceramic waste-added) 2, 7, and 28-day strengths are lower than the reference cement. However, it was determined that all cement samples with CSW in the strength class of 42.5 MPa is within the appropriate values (≥42.5 and ≤62.5) according to the conformity criteria TS EN 197-1 standard. If the effect of CSW substitution on 2-, 7- and 28-day compressive strengths is analysed separately, there was a similar decrease in 2- and 7-day compressive strengths (12%, 8%, respectively) up to 12% CSW substitution compared to the R, after 14% there was a significant decrease (21%, 14%, respectively). On the other hand, the use of CSW affected the 28-day compressive strengths less than the 2 and 7-day early strengths. The 28-day compressive strength of SW4 changed by 3%, while that of SW18 changed by 15%. Furthermore, the 32 µm sieve balance of the reference cement was found to be 18.6% when grinding was done.

4. Conclusions

In this study, it is aimed to investigate the usability of CSW instead of reducing the use of clinker to minimize energy consumption and CO2 emission during cement production. For this purpose, the optimum parameters for grinding clinker under laboratory conditions were determined by the Taguchi method in the first stage. Blended cements with CSW additives were produced with these specified conditions.

When all the data were examined, optimum conditions were determined to produce cement with only 9 experiments using the Taguchi method (60 minutes of grinding at a 26% fill rate and consisting of balls in the fine-size ball weight group). According to these conditions, one reference cement and nine blended cements with CSW were grinded. Analysis showed that 2-, 7-, and 28-days compressive strength of all these samples remain the appropriate values of the standard. It has been concluded that CSW can be substituted up to 18% instead of clinker, thus reducing the energy consumed and the CO_2 emission released to produce clinker in the kiln.

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