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RESEARCH ARTICLE

The influence of cement kiln dust on strength and durability properties of cement-based systems

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Abstract

There are very few studies in the literature on the usage of CKD in cementitious systems. This article presents the laboratory study results on the influence of cement kiln dust (CKD) on the properties of mortar made with cement kiln dust and Portland cement. The article aims to prevent CKD's (known as a hazardous waste product) damage to nature by utilizing CKD in cementitious systems and contributing to sustainability by reducing cement amount in the cementitious system. For this purpose, 5%, 10%, 15%, and 20% of CKD were replaced with cement and binary cementitious systems were formed. For all mortar mixes, the water/binder ratio was kept constant at 0.5, and the sand/binder ratio was 3. Workability, dry unit weight, water absorption ratio and porosity, flexural strength, compressive strength, abrasion, carbonation, and high-temperature resistance tests were performed on the mortar specimens. Based on the results of laboratory work, it was observed that the replacement of CKD with cement reduces the workability of fresh mortar. Compressive and flexural strengths of CKD-added mixtures were found to be equivalent or insignificantly lower than that of the control sample. The addition of CKD had a negligible effect on water absorption and porosity of samples. Besides, the residual compressive strength determined after the elevated temperature test for the sample made with CKD were found to be equivalent or higher compared to the control sample. Present laboratory studies showed that utilization of CKD in cementitious mortar system is feasible in terms of testing conducted.

Keywords Cement kiln dust · Cementitious material · Strength · Mortar

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Highlights

- The addition of cement kiln dust had insignificant effect on the water absorption capacity and porosity in comparison to control mortar.
- The addition of CKD up to 20% as cement replacement in mortar showed higher or equivalent flexural and compressive strengths compared to control mortar.
- CKD-added mortars showed similar elevated temperature resistance to control mortar.
- Abrasion resistance of all CKD replaced mortar increased in comparison to control mortar.
- CKD can be blended with cement in the factory.

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Introduction

Global cement production has exceeded 4 billion tons due to the acceleration of social development and changes in our lives (Ren et al. 2021). Cement is produced by calcination of calcium carbonated and alumina siliceous materials together. During calcination process, calcium carbonated matter ($CaCO_3$) was disintegrated into CaO and CO_2; thus, it results with CO_2 emission to the atmosphere. A high amount of CO_2 is released to nature during Portland cement clinker production worldwide, such that the CO_2 gas released during clinker production is approximately 5–7% of the total CO_2 emissions into nature (Deja et al. 2010; Benhelal et al. 2013; Atiş et al. 2015; Durak et al. 2021). This high carbon dioxide emission, which has a significant impact on global warming and climate change, is a severe issue for societies (Chen et al. 2019; Shuai et al. 2019; Zhang et al. 2020; Bildirici 2020). Moreover, Portland cement production of the factors contributes to an unhealthy environment. The World Health Organization reported that 7 million people die each year as a result of working or living in a hazardous environment. This rate accounts for 23% of adult deaths and 26% of child deaths under the age of 5 (Bildirici 2020).

Furthermore, it has been stated that cement production is an energy-intensive industry (Bildirici 2020), accounting for 5–12% of total industrial energy consumption which contributes to CO_2 emissions (Ali et al. 2011).

During the traveling of raw material through the rotary Portland cement kiln system, some particles originating from clinker production are entrained in the combustion gases flowing countercurrent to the feed. These particles are called CKD (Maslehuddin et al. 2008). CKD is composed of fine, powdery solids and highly alkaline particles (Kim and Jung 2020), and it is similar to Portland cement (Seo et al. 2019). Cement Kiln Dust (CKD) is a hazardous by-product produced in vast amounts during Portland cement production (Yaseri et al. 2019). CKD amount is estimated to be approximately 15 to 20% relative to clinker production (Kunal and Rajor 2012). Every year, millions of tons of CKD are manufactured worldwide, with most of them sent to landfills. This waste material causes environmental pollution as well as ground water pollution due to rainfall (Kunal and Rajor 2014).

Ravindrarajah investigated usage of cement kiln dust in concrete. He indicated that cement may be safely replaced with CKD up to 15% in terms of short-term strength and that using CKD can reduce building costs (Sri Ravindrarajah 1982).

Parham et al. carried out a laboratory study to investigate the addition of CKD in ordinary and lightweight concrete. They reported that concrete containing CKD presents lower workability and modulus of elasticity; however, improvements in strength were observed by adding particular amounts of CKD. They concluded that adding 10% of CKD as a replacement of cement is the appropriate amount for using in ordinary and lightweight concrete (Shoaei et al. 2017).

Yaser et al. studied the usage of normal and treated cement kiln dust as cementitious materials in concrete as cement substitution. They concluded that utilizing 10% of CKD with cement is appropriate amount in concrete production (Gamil et al. 2019).

Mohamed et al. carried out a study to evaluate to recycling of high amount of cement kiln dust in bricks industry. As a result of their laboratory study, they highlighted that it is possible to recycle large amount of CKD in cement bricks manufacturing. They concluded that up to 50% CKD could be substituted with cement in load bearing unit production. It can also be used with sulfate resisting cement (El-Attar et al. 2017).

Al-Harthy et al. investigated the effect of cement kiln dust on mortar and concrete mixtures. They replaced the CDK with cement at the ratios of 5%, 10%, 15%, 20%, 25%, and 30%. According to test results, samples containing lower percentages of cement kiln dust gave equivalent compressive and flexural strength to the reference sample. Moreover, they asserted that while the inclusion of CKD did not affect the unit weight of the samples, it decreased the sorptivity value of specimens (Al-Harthy et al. 2003).

Maslehuddin et al. studied on properties of cement kiln dust concrete. They replaced CKD with cement at the ratio of 5%, 10%, and 15%. They concluded that 5% replacement of CKD did not significantly differ compressive strength from control mixture. However, 15% replacement of CKD decreased the compressive strength remarkably in the order of 14% (Maslehuddin et al. 2009).

Kunal et al. carried out a review study on use of cement kiln dust in cement concrete and its leachate characteristics. They concluded that mortars and concrete mixtures containing 5–10% of CKD gave nearly equivalent compressive and flexural strength and durability-related properties as that of the reference mixture (Kunal and Rajor 2012). Similar conclusion was also made by Rafat Siddikue carried out a review study on utilization of cement kiln dust (CKD) in cement mortar and concrete (Siddique 2006).

It is known that CKD is a waste material causing environmental problems. Utilization of CKD in cement based material as cement replacement can help to reduce its environmental problems not only by utilizing CKD but also reducing cement used in the mortar productions. Relevant literature review showed that a limited number of studies have been conducted investigating the effect of CKD addition on the strength and particularly durability of cementitious systems. The present experimental study aims to reduce the cement amount in the system by including CKD as waste material in the cement-based systems, and investigate the effect of CKD on the durability-related properties of mortar. For this purpose, 5, 10, 15, and 20% CKD were replaced with Portland cement. Workability, unit weight, water absorption capacity, porosity, flexural strength, compressive strength, abrasion, carbonation, and high-temperature resistance of cementitious systems were investigated.

Experimental study

Materials

Portland cement

Portland cement (PC) CEM I 42.5 R was used in all of the mixtures. The chemical oxide composition of PC was given in Table 1. The Blaine specific surface area and the specific gravity of PC used in the research were 2960 cm^2/g and 3.21 g/cm^3, respectively.

Table 1 Chemical composition of Portland cement (%)

	SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	$Na_2O+0.658\ K_2O$	MgO	LOI
Cement	20.37	5.29	3.73	62.02	2.4	0.53	1.0	0.9

Table 2 Oxide composition of cement kiln dust (%)

	SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	Na_2O	K_2O	MgO
Cement kiln dust	20.87	5.31	3.39	64.46	-	0.29	0.74	3.67

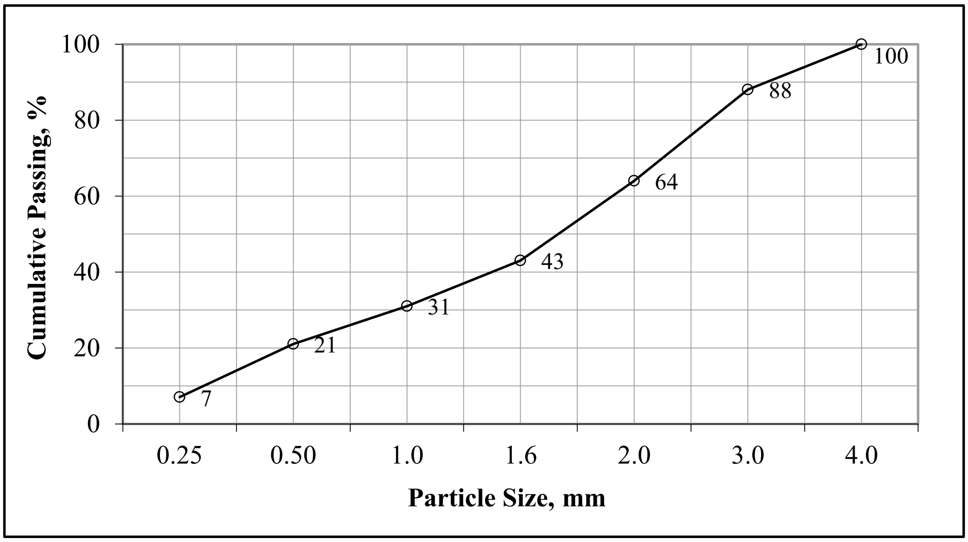


Fig. 1 Aggregate size distribution

Cement kiln dust

Cement kiln dust (CKD) was supplied by the ÇİMSA Cement Factory in Kayseri, located in middle of Turkey. CKD was a fine gray-black powder with a consistent particle size distribution. Its oxide composition was presented in Table 2. The Blaine specific surface area and the specific gravity of PC used in the research were 3460 cm^2/g and 3.23 g/cm^3, respectively.

Sand

Natural river sand (0–4 mm) was used as the fine aggregate to prepare the mortar samples. The aggregate size distribution curve is given in Fig. 1. The fineness modulus of the river sand was 1.46 and its specific gravity at SSD condition was 2.5 g/cm^3. The water absorption ratio of sand was 1.46%.

Mix proportion

Mortar mixes were prepared with 5, 10, 15, and 20% of cement replacement by CKD in mass basis. M0 is a control sample poured with just Portland cement. In this research, mortar mixtures were made with the same sand/binder ratio of 3, and the constant water/binder ratio of 0.50 were for all mixtures. Details of the mix design of cementitious systems are shown in Table 3.

Table 3 Mix design of cementitious systems (g)

Notification	PC	CKD	Sand	Water
M0	450.0	0	1350	225
M5	427.5	22.5	1350	225
M10	405.0	45.0	1350	225
M15	382.5	67.5	1350	225
M20	360.0	90.0	1350	225

Mixing procedure

The cement and cement kiln dust were mixed according to TS EN 196–1 (TS EN 196-1 2016) in a Hobart type mixer. The fresh mortars were placed into molds in two layers. For the abrasion test, cubic samples were prepared by pouring them into three-cell cube molds of 71 × 71 × 71 mm^3 dimensions. For other laboratory experiments, 40 × 40 × 160 mm3 prismatic three-cell molds were used. Specimens were demolded one day after casting; then, mortar specimens were cured in the water tank at ambient temperature (21 ± 1 °C) until the testing days.

Testing

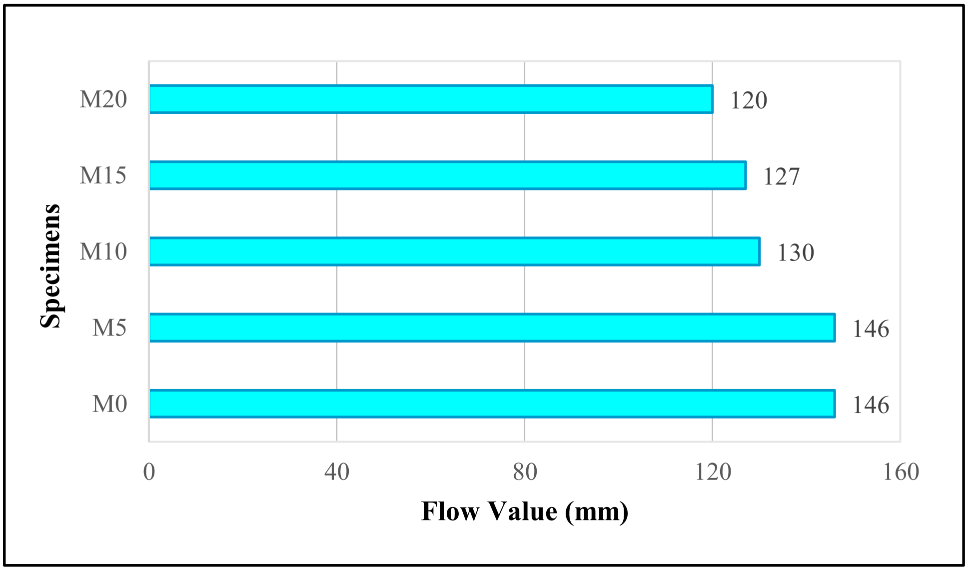
The workability of the mortars was tested on a flow table in compliance with TS EN 1015–3 (TS EN 1015–3 2000). The flow diameter of the fresh mortars was measured in two perpendicular directions and the average of them was determined. To determine the unit weights of the specimens, the specimens were removed from the water tank after 28 days and dried in the oven and their weights were measured. Water absorption ratio and porosity tests were performed on the 40 × 40 × 160 mm3 mortar samples on the 7th, 28th, and 90th days. Flexural and compressive strengths of all mortar mixtures were tested on the 7th, 28th, and 90th days in accordance to TS EN 1015–11 (TS EN 1015–11 2020) to investigate strength development. The carbonation test was conducted on prismatic samples stored in a room conditions for 18 months. To determine the elevated temperature resistance of mortars, 40 × 40 × 160 mm prismatic samples cured for 28 days in water were exposed to 300 °C, 600 °C, and 900 °C temperatures. The oven temperature was gradually increased by 2.5 °C per minute until the testing temperature was reached. When the oven reached the test temperature, samples were kept at the target temperature for 2 h. The oven was then switched off. The samples were left to cool in the oven, avoiding rapid temperature changes. After the specimens were cooled to room temperature, flexural and compressive strength tests were performed on the samples. The abrasion resistance of the mortar samples was determined in accordance with TS 2824 EN 1338 (TS 2824 EN 1338 2005) on cube samples of 71 × 71 × 71 mm. Before beginning the experiment, sample weights were recorded and height measurements were measured from a total of 9 points on the sample. The device was started after 20 g of artificial corundum powder was placed on the friction path. The disc applied a 294 N abrasion load to the cubic specimen. The machine was turned off after 22 cycles, and the corundum powder was refreshed. The sample was rotated 90° clockwise. The disc and contact surface were cleaned each time, and the 2nd, 3rd, and 4th surfaces were abraded in this method, finishing the first stage after 88 cycles. Each sample was subjected to a total of 352 cycles during the study. The original weight and volume of the samples were used to determine the specimen's density. Weight loss was calculated as the difference between the initial and final weights measured after the experiment. The volume loss of the sample was determined by dividing weight loss by density. The volume loss found as a result of the calculations was accepted as the abrasion of the sample.

Results and discussion

Workability

Flow table workability tests results are demonstrated in Fig. 2. The flow value of the control mixture (M0) is 146 mm. The workability of the sample containing 5% CKD was the same as the workability of the control sample. However, as the amount of CKD increased, the workability of the fresh mortar decreased. Workability values of mixture made with 10%, 15%, and 20% CKD were 130, 127, and 120 mm, respectively. A significant decrease was observed in the workability of mortars with substitution of CKD in comparison to the control mixture. It was observed that the

Fig. 2 Flow values of mortars



mixture with the lowest workability was the mortar containing 20% CKD. It is known that total CaO component of CKD comprise of free lime. When this free lime encounter with water, they react with each other rapidly. Thus, reaction consumes water in the mixture, resulting with rapid setting and lower workability (Najim et al. 2014).

Unit weight

Dry unit weights of mortar samples are presented in Fig. 3. The dry unit weight of the control sample was determined as 2.04 g/cm^3 whereas the dry unit weights of mortars incorporating CKD ranged between 2.03 and 2.05 g/cm^3. In Fig. 3, it is seen that the 5%, 10%, 15%, and 20% addition of CKD did not change the dry unit weights of the samples and the results were similar to the control sample. It can be said that the addition of CKD does not affect the dry unit weight values of the samples. This is explained by CKD and Portland cement showing equivalent specific gravity value. Result of Al-Harthy et al. showed that unit weight of CKD containing mixture (replacement ratios of 5%, 10%, 15%, 20%, 25%, and 30%) did not differ from unit weight of control mixture (Al-Harthy et al. 2003).

Water absorption ratio and porosity

The results of the water absorption test carried out on prismatic samples cured for 7, 28, and 90 days are shown in Fig. 4. The water absorption rates determined were between 9.0 and 9.2% for the samples cured for 7 days. The water absorption rates decreased for the samples cured for 28 days in comparison to 7 days of curing; these values were between 8.2 and 8.5%. The lowest water absorption rates were measured at 90 days of cured samples and ranged from 6.4 to

Fig. 3 Dry unit weight of mortars

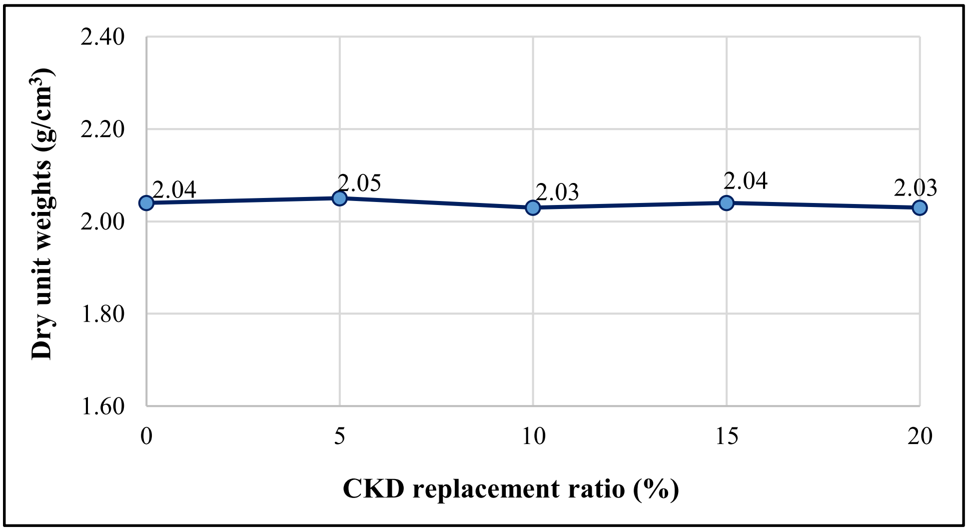
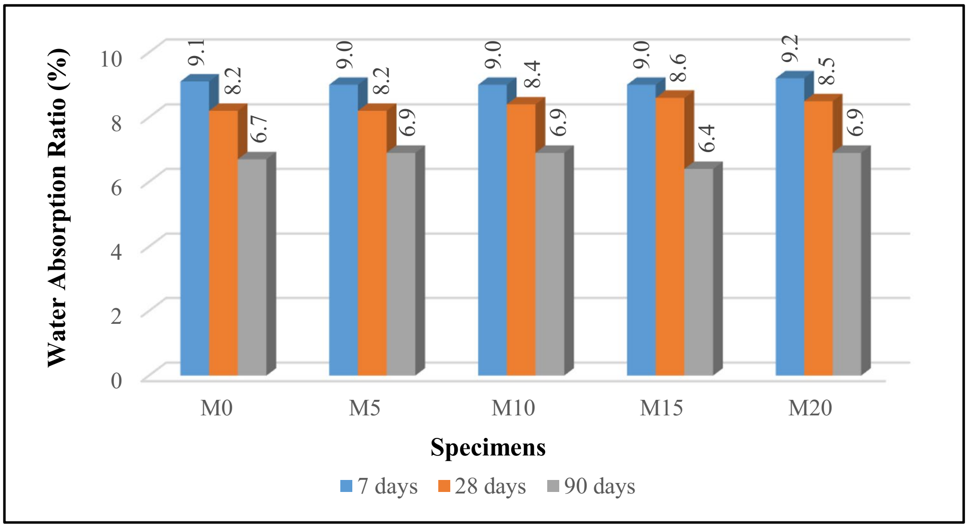


Fig. 4 Water absorption ratio (%)



6.9%. The water absorption rate decreased as the curing time of the samples increased. Still, it was observed that the addition of cement kiln dust had an insignificant effect on the water absorption ratio. This is attributed to the ongoing hydration reaction of the binder, the longer the curing time the more hydration product that fills the pore of the matrix causing lower porosity.

The porosity test results carried out on mortars cured for 7, 28, and 90 days are shown in Fig. 5. For 7-day cured samples, the porosity values were between 18.2 and 18.5%. For 28-day cured samples, the porosity values decreased and ranged between 16.6 and 18.8%. The lowest porosity ratios were observed for the 90-day cured samples and ranged from 13.2 to 14.0%. The hydration process of cement in mixtures was the reason why both the water absorption rates and the porosity decrease as the curing times of the samples increase; as the amount of hydration product increases, more C-S–H gel is produced and the pore volume decreases as the voids are filled with gel (Yamanel et al. 2019).

A comparison was made between absorption values of control mortar and CKD containing mortar showed that inclusion of CKD as cement replacement material did not impair absorption characteristic of mortar. Furthermore, it was observed that CKD has a tendency to improve water absorption properties of the mortar. Similarly, CKD containing mortar showed better or equivalent porosity characteristic in comparison to mortar made without CKD. Therefore, it was concluded that CKD inclusion in mortar gave equivalent absorption and porosity values to Portland cement mortar. This conclusion was supported by published literature, for instance, Al-Harthy et al. (Al-Harthy et al. 2003) studied on sorptivity and absorption test to compare the absorption properties of mortar samples made with and without CKD. They reported that sorptivity of mortar decreased with CKD incorporation (up to 30%) in mortars compared to the control mortar. They stated that without affecting strength due to inclusion of CKD, improving absorption properties of mortars means that enhancing the durability.

Flexural strength and compressive strength

Flexural strengths of mortars are demonstrated in Table 4. As a result of the replacement of 5%, 10%, 15%, and 20% CKD by weight with cement, the flexural strengths of the samples on the seventh day increased by 3.3%, 11.7%, 3.3%, and 11.7%, respectively, compared to the control sample. Hence, it was seen that CKD positively affected the on flexural strength of samples cured for 7 days. With the addition

Fig. 5 Porosity (%)

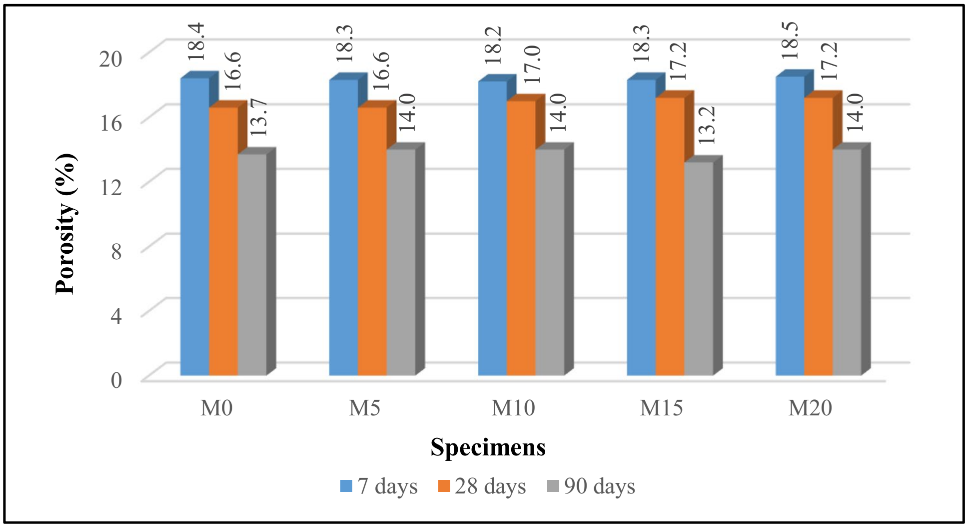


Table 4 Flexural and compressive strengths

Specimens	Flexural strengths (MPa)			Compressive strengths (MPa)		
	7d	28d	90d	7d	28d	90d
M0	6.0	6.8	8.3	33.1	42.9	49.5
M5	6.2	7.5	8.8	36.2	46.4	52.9
M10	6.7	6.9	8.4	35.4	43.2	50.6
M15	6.2	6.4	8.2	35.9	41.7	48.1
M20	6.7	6.9	7.7	33.5	41.7	47.3

of 5% and 10% CKD to the system, the flexural strengths at 28 days increased by 10.3% and 1.5%, respectively, while the flexural strengths at 90 days increased by 6.0% and 1.2%, respectively. On the other hand, the inclusion of 15% and 20% CKD as cement replacement showed an insignificant decrease in flexural strength in comparison to the control mixture at 28 and 90 days of curing time. These flexural strength values can be considered equal to the flexural strength of control sample.

All CKD dosages used in the study contributed to the increment in compressive strength in 7-day samples. By replacing 5%, 10%, 15%, and 20% CKD with cement, the compressive strength of the specimens at 7 days increased by 9.4%, 6.9%, 8.5%, and 1.2%, respectively, compared to the control sample. It can be seen from Table 4 that the compressive strength of the M5 sample increased by 8.2% on the 28th day and 6.9% on the 90th day compared to the control sample. Also, the compressive strength of the M10 sample increased by 8.2% on the 28th day and 6.9% on the 90th day compared to the control sample.

Maslehuddin et al. reported based on their results that utilizing 5% CKD as replacement of cement result with approximately 4% increase in compressive strength. Moreover, 15% CKD replacement result approximately 14% decrease in compressive strength in comparison to reference mixture (Maslehuddin et al. 2009).

As mentioned in the “Introduction” section, Kunal and Rajor (2012) and Rafat (Siddique 2006) reported that mortars and concrete mixtures containing 5–10% of CKD gave nearly equivalent compressive and flexural strength and durability-related properties as that of the reference mixture.

Although, majority of references suggested to utilized CKD as cement replacement in the order of 5% or 10%, the current study showed that, replacing CKD with cement at 15 and 20% caused insignificant and negligible decrease in compressive strength. Therefore, based on strength results, up to 20% CKD replacement with cement seems to be feasible in concrete production.

It should be noted that CKD amount is estimated to be approximately 15 to 20% relative to clinker production (Kunal and Rajor 2012). Since chemical oxide composition of cement and CKD can be considered equivalent (see Tables 1 and 2), thus, it is concluded that there is no need to send the CKD to landfill area; they can be blended with cement in the cement factory.

Carbonation

The penetration of CO_2 gas into the mortar causes carbonation, which is related to the permeability and porosity of the mortars. It is known that the carbonation depth of mortars depends on the curing condition, the water/binder ratio, the ambient temperature, and the relative humidity at which the mortars are exposed to carbonation. Figure 6 shows the carbonation depth of mixtures. According to Fig. 6, the lowest carbonation depth was measured from the control sample. It can be seen from Fig. 6 that the depth of carbonation increased as CKD amount increased in the cementitious system. Therefore, the highest carbonation depth was observed in the M20 sample. This is attributed to not only porosity of the mortars but also gas permeability of CKD content in the mortar resulted in higher porosity and permeability. As a result of the increment in porosity and permeability, more CO_2 gas penetrated the sample and reacted with Portlandit ($Ca(OH)_2$), causing higher carbonation depth. Carbonation can be considered harmful for reinforced steel embedded in concrete (causing corrosion). On the other hand, when steel is not used in mortar, carbonation can be regarded as

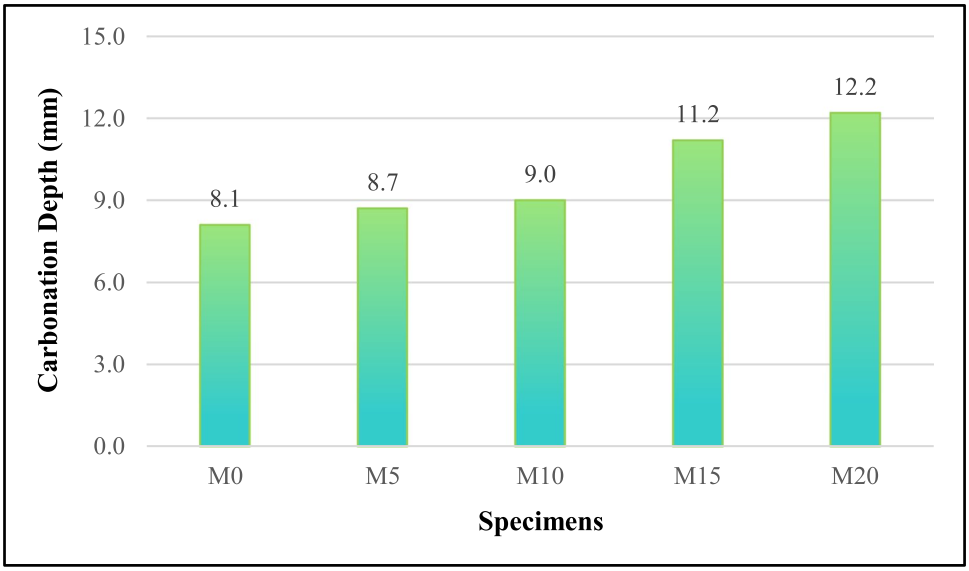


Fig. 6 Carbonation depth of samples after 18 months

beneficial for concrete strength and CO_2 absorption from the atmosphere.

Elevated temperature resistance

Prismatic samples with dimensions of 40×40×160 mm^3 were exposed to elevated temperatures at 300 °C, 600 °C, and 900 °C for a specific duration. The relative residual flexural and compressive strengths of the samples exposed to 300 °C, 600 °C, and 900 °C are presented in Table 5. The flexural strengths and compressive strengths of the samples cured in water on the 28th day were taken as reference, and relative residual flexural and compressive strengths were calculated by dividing the strength of samples exposed to the elevated temperature by the reference sample.

A closer look to Table 5 shows that elevated temperature influences the flexural strength more than the compressive strength of the mortar. Mortars containing 5%, 10%, 15%, and 20% CKD did not lose much strength after being exposed to 300 °C. However, when elevated temperature increased to 600 °C, then the flexural and compressive strength of cementitious systems were significantly reduced due to disintegration of cementitious matrix. On the other hand, there were no strength results obtained for the samples exposed to 900 °C, due to the extensive damage on the samples. It was observed from Table 5 that addition of CKD in mixtures reduced residual flexural and compressive strengths, negligibly.

Abrasion testing

Abrasion tests were carried out on 71×71×71 mm samples cured for 7, 28, and 90 days. Abrasion losses of mortar produced were determined as mass loss (g), presented in Fig. 7. Control M0 sample showed the highest mass loss. The weight loss of 7-day cured M0, M5, M10, M15, and M20 samples made with and without CKD was 33.5, 31.1, 30.2, 28.7, and 29.4 g, respectively. The weight loss of 28-day cured M0, M5, M10, M15, and M20 samples made with and without CKD was 31.6, 24.4, 22.5, 23.2, and 24.1 g, respectively. The weight loss of 90-day cured M0, M5, M10, M15, and M20 samples made with and without CKD was 29.8, 22.7, 22.2, 21.9, and 22.7 g, respectively. When 5%, 10%, 15%, and 20% CKD were added to the system cured for 7 days, the weight losses of the samples decreased by 7%, 10%, 14%, and 12%,

Table 5 Relative residual flexural and compressive strengths after elevated temperature

Specimens	Flexural strengths (%)			Compressive strengths (%)		
	300 °C	600 °C	900 °C	300 °C	600 °C	900 °C
M0	90	19	0	95	35	0
M5	94	18	0	93	37	0
M10	84	20	0	92	39	0
M15	86	17	0	95	37	0
M20	87	20	0	90	38	0

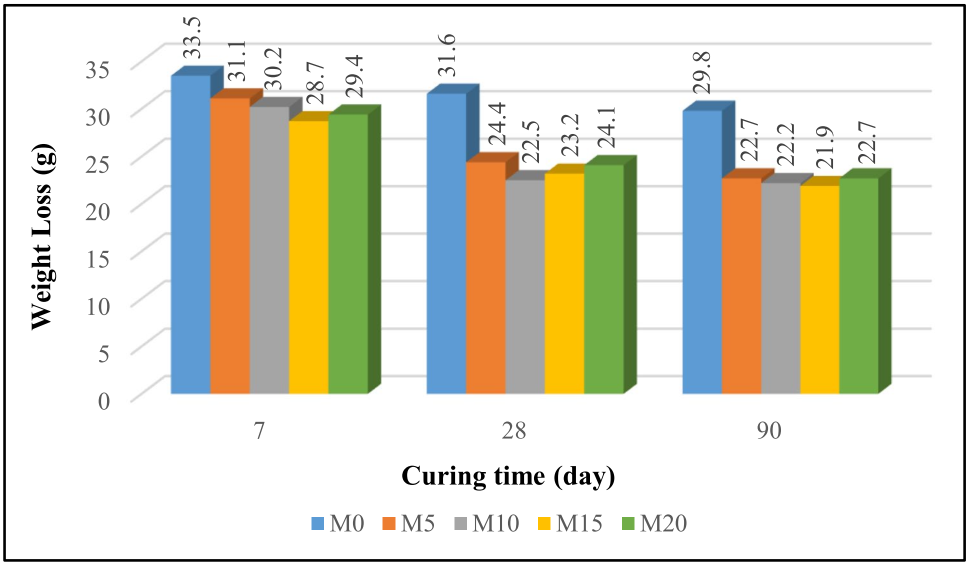


Fig. 7 Weight loss after abrasion test

respectively, compared to the control mortar. In general, mass loss decreased as the amount of CKD increased. Furthermore, when considering in the 90-day cured samples, 5%, 10%, 15%, and 20% CKD addition resulted in a 24%, 26%, 27%, and 24% reduction in mass loss, respectively. As the curing time increased, the favorable influence of CKD on abrasion resistance became more pronounced. The abrasion of all samples is reduced as the curing time increases. The reason for this situation is the decrease in porosity and increase in strength due to the formation of hydration products in the cementing system (Yamanel et al. 2019).

Conclusion

Based on this experimental study, the following conclusions were made:

- The workability of mortar decreased by addition and increasing replacement ratio of CKD with cement.
- The addition of CKD had almost no effect on dry unit weight values of cement-based specimens.
- The addition of cement kiln dust had insignificant effect on the water absorption ratio and porosity in comparison to the control mortar. The water absorption rate and porosity values decreased as the curing time of the samples increased. This is attributed to the ongoing hydration reaction of the binder. The longer the curing time the more hydration product fills the matrix pore, causing lower porosity.
- The addition of CKD up to 20% as cement replacement in mortar showed higher or equivalent flexural and compressive strengths than the control mortar.
- Replacement of CKD with cement did not cause much strength loss after exposure to 300 °C and 600 °C compared to the control mortar. When elevated temperature was 600 °C, the flexural and compressive strength of cementitious systems were significantly reduced concerning 300 °C. There were no strength results obtained for the samples exposed to 900 °C due to the extensive damage on the samples.
- Abrasion resistance of all CKD replaced mortar increased in comparison to the control mortar.
- Experimental studies have shown that almost equivalent test results can be obtained by replacing CKD with cement up to 20%. Also, the chemical oxide composition of cement and CKD can be considered equivalent. For this reason, it was concluded that CKD could be used up to 20% by blending it with cement in the factory.

Author contribution Hadiye Hakkomaz: investigation and experiment; Hediye Yorulmaz: literature search and writing; Uğur Durak: literature search and writing; Serhan İlkentapar: experiment; Okan Karahan: idea for research and writing; Cengiz Duran Atiş: writing and revised the manuscript critically.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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