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Determining the Ultrasonic Pulse Velocity (UPV) of Cement Mortar with Partial Replacement of OPC with CKD and SF

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Abstract. A significant number of researches pointed to the serious environmental and health effects of the Ordinary Portland Cement (OPC), including the harmful emissions and alkaline wastewaters. Therefore, the development of eco-friendly alternatives for the OPC is one of the priorities of nowadays studies. However, the suggested eco-friendly alternatives to the OPC might possess negative influences on the properties of the concrete. This research aims at investigating the applicability of by-product materials, such as cement kiln dust (CKD) and silica fume (SF), as an alternative to OPC in the cement mortars. The mortar specimens were mixed with 0 to70% CKD with SF (equal values) as a partial replacement for cement. The hardening samples have been tested by the UPV test at ages 1 week to 4 weeks. The results indicated that high ratios of CKD and SF replacements result in a slight decrease in the pulse velocity of specimens, while small replacement ratios show improvement in these properties. Time of curing is very important in improving the properties of the hardening mortars. Using a small amount of CKD and SF (20-30%) could improve the durability of cement mortars and it seems to be reasonable value in mixers.

1. Introduction

In this era, concrete has vital importance in the construction industry, and the Ordinary Portland Cement (OPC) is the most important ingredient of the concrete mix [1]. Despite the vital role of the cement in maintaining the civilization and the global economy, its role in the deterioration of the environment and consequently is well-proved [2]. Where, the reports indicated that the cement factories emit carbon dioxide amount equivalent to 6 to 8% of the whole carbon dioxide in the air [3, 4], which causes tragical effects on the environment, such as global warming [5-8]. The latter led to huge changes in water consumption [9-11] and wastewater pollution [12-14]. Moreover, due to the chemical composition of OPC, the disposed of wastewaters from the concrete plants and casting processes is very basic (pH of 10 to 12) [15, 16], which results in tragical impacts on the quality of water bodies and mass killing of living cells in that bodies [17-19]. Thus, many management plans [20-22], and water/wastewater treatment methods were developed to remove many of the pollutants that could be found in effluents of concrete plants, such as turbidity [23-26], phenols [27-29], metals [30-34], phosphate [35-41] and nitrates [42-45]. However, these methods still not enough to control the whole expected pollution from concrete plants [46-51]. Due to a large amount of carbon dioxide and wastewaters released from cement-related activities to the atmosphere and water bodies, the production of cement has become a growing concern.

Therefore, the scientists believe that the sustainable solution for the problems of the cement industry is the development of alternatives (cementitious materials) that replaces as a part of cement such as cement kiln dust (CKD) and silica fume (SF) [1, 52].

It is known that the utilisation of CKD and SF do exert undesirable effects on cement mortars, On the other hand, these materials may improve the performance of these mortars. Generally, the fresh mixes' workability reduced when the percentage of the CKD/cement increased. In addition, the compressive strength of the mortar also reduces by increasing CKD [1]. The pozzolanic materials, such as SF that is ultrafine powders, are very reactive and widely applied in concretes due to their huge surface areas and their good content of silica oxides [16]. It is found that SF can be used to replace the OPC by around 0.25 to 0.33 (mass ratios) without decreasing the strength [4].

The ultrasonic pulse velocity (UPV) is an *in situ*, non-destructive testing method to measure the quality of concrete-based structures. In this method, the strengths and qualities of concretes are evaluated by calculating the velocity of the UPV that passed via concretes [16].

In this study, the performance of CKD and SF as a replacement for OPC (at different ratios) were assessed. The main goal of this study is to examine the effects of the use of these materials on the durability of the cement mortar at different curing ages (7, 14, and 28 days) by employing an ultrasonic pulse velocity (UPV) test.

2. Experimental program

In these experimental investigations, many tests were conducted to measure the ultrasonic pulse velocity of the cement mortar made by partial replacement of OPC with CKD and SF. Mix design and the percentages of CKD and SF that are used in this investigation are disused later.

2.1. Materials

The CKD is an industrial by-product of the cement industry, where it disposes of it by landfill. The CKD is a fine powdered material that contains reactive Ca oxides, and its main properties depend on the locations within the collection system, the kind of operations, the dust-collection facilities, and the types of fuels used in the production process. CKD contains un-reacted raw feeds, partially calcined feeds and clinkers dust, free limestone residuals, and salts of alkali sulphates, halide, and other volatile compounds. It could be used with FA and GGBS up to 15% by mass of cementitious materials. When CKD is used alone, the obtained mortar may suffer from a reduction in workability, setting time, and strengths because of the high alkali contents.

Silica fume (SF) is also a by-product of silicon metals production. It is widely applied in concrete as a mineral addition as its chemical and physical properties are favorable for cementitious reactions. When the SF is added to the concrete, its strength increases dramatically and it can improve the durability of concrete. In the silicon metal and alloys industry, the smokes that emitted from furnaces operation are collected as SF, rather than disposing of them in landfills. SF particles are very fine with an average size equals to about 1/1000th of the mean sizes of the cement particles. Therefore, it is a very reactive pozzolanic material when applied in concretes due to its micro-size, and high surface area, and silica oxides contents.

In this study, the Ordinary Portland cement (OPC) was used as the main binder due to its good adhesive characteristics that serve its bonding with other components of the mixture. The cement used in this work was tested according to BS EN 196-2:2013.

The chemical properties of OPC and SF are listed in Table 1. These properties are fulfilled to BS-EN-197-1(2011), and BS-EN-450-1(2012).

In this study, local clean river sands were used as fine aggregates (particle sizes <5mm). The grains size distributions, and chloride and sulphate contents were measured according to the BS EN 12620:2002+A1(2008).

Also, the portable water free from organic particles was used for mixing as well as curing of concrete.

Table 1. Chemical compositions of OPC, CKD, and SF.

Chemical composition (%)	Sample		
	OPC	CKD	SF
SiO_2	20.48	12.27	93.79
Al_2O_3	15.06	2.27	0.36
Fe_2O_3	5.23	3.70	1.48
CaO	62.72	45.28	0.33
MgO	3.40	1.49	0.41
SO_3	2.12	2.59	0.19
Na_2O	0.18	0.31	0.43
K_2O	1.67	5.68	0.62
Cl	0.02	8.06	0.05
L.O.I	0.33	17.38	1.63

2.2. Test methods
To examine the effect of partial replacement of OPC by CKD and SF on the strength of the mortar mix, three prisms (160x40x40 mm) were cast for each case. These cases include testing the samples poured from the mortar of cement only. Then, the tested specimens consist of cement with three ratios of CKD and SF. All samples were kept in appropriate condition and after 1 day of casting, they demolded and placed in water for curing. Later, the ultrasonic tests were conducted on hardening samples at 7, 14, and 28 days according to BS EN 12504-4:2004.

2.3. Mix Design
In this experimental program, the design procedure includes pouring the control cement mortars by choosing the amount of cement, water, fine aggregate, and mineral admixture materials. The fine aggregates were selected to match the standard grading curves in the design of mixtures. The water to binder (cement + CKD +SF) ratio is taken 0.4 for all the mixes. While the proportion of sand to binder was one part of cement to 2.5 parts of sand. The weight of each component/ingredients and the mix design proportion is tabulated in Table 2.

Table 2. Mix design.

Mix No.	OPC (%)	CKD (%)	SF (%)
1	100	0	0
2	70	15	15
3	50	25	25
4	30	35	35

UPV test is commenced by emitting ultrasonic pulses via the sample to be examined and calculating the required time by the pulse to penetrate the sample (direct method). High velocity indicates good quality of the concrete sample, while slow velocity indicates a bad quality of the concrete sample. UPV testing equipment/tools include pulses generators, a transducer for the transformation of the electronic pulses into mechanical pulses having oscillations from 40 to 50 kHz, and a pulses receiver. Pulses velocities are calculated as follows:

$$\text{Pulse velosity} = \frac{\text{The thickness of the sample}}{\text{The required time for the pulse to penetrate the sample}} \quad (1)$$

3. Results

The results of the conducted tests of a control cement mortar with partial replacement of OPC with various percentages of CKD and SF, at different curing periods, are listed in Tables 3 and Figures 1 and 2.

Table 3. UVP test at ages of 7, 14, and 28 days.

Test No.	OPC (%)	CKD (%)	SF (%)	UPV test (km/s)		
				7 days	14 days	28 days
1	100	0	0	3.815	3.904	3.977
2	70	15	15	3.824	3.969	4.045
3	50	25	25	3.465	3.677	3.796
4	30	35	35	3.033	3.276	3.546

From these results, it can be observed:
(i): It can be seen that using a partial replacement of CKD and SF in mixes leads generally to a slight decrease in the pulse velocity values of cementitious mortar. However, it is obvious that mix 2 shows an increase in the pulse velocity values when compared with others including the first mix. For instant, at 28 days of curing, the change in pulse velocity values for the three mixes in comparison with the first mix were +2%, -5%, and -11 % respectively (Figures 1 and 2). This could be explained that the small amount of cementitious materials could fill the voids in the mortar and then improve the mechanical properties of it.

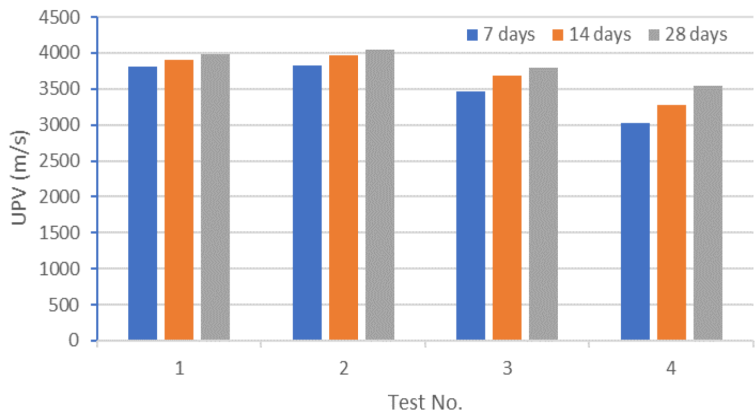

Figure 1. UPV test for mixes at ages 7,14 and 28 days.

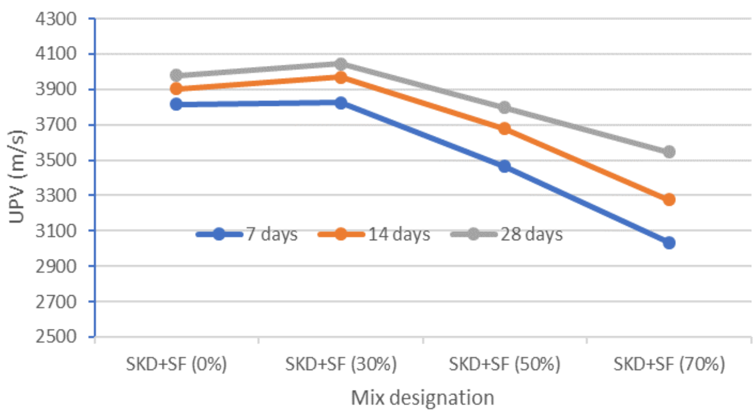

Figure 2. Effect of partial replacement of CKD and SF on durability of mix.

However, it is clear, for example, that using 70% of a partial replacement material results in dropping the pulse velocity values of mortar by around 20% at 7 days. On the other hand, this ratio decreased to

be 11% at 28 curings because the CKD and SF are inactive material at an early age and they need time to interact with the components of a cement. In summary, the partial replacement of CKD and SF can be done between 20 to 30% to get good durability and reduce environmental pollution. This can be attributed to the fact that the SCMs reduces the compressive strength of cementitious mortar which is a significant factor in production gel (C-S-H) in mortar. Because of these react after hydration of cement and use the hydration products, $Ca(OH)_2$ to active and start the hydration of CKD and SF.
(ii): The results show higher pulse velocity values for samples are curing 28 days. This can be explained by the fact that the curing age affects gain and increase of C-S-H that leads to reduce the volume of internal voids or porosity in the structure of mortar that in turn affects the density of concrete and increase of compressive strength of these mixes. For example, the percentages increase in pulse velocity values for mix 4 at 14 and 28 days were 8% and 16% respectively compared with the same samples at 7 days.
The applied method in this study was the Ultrasonic Pulse Velocity (UPV), which could be categorized as a traditional method, therefore; more advanced methods are recommended to check the properties of mechanical properties of concrete. In this context, sensors were applied in the previous studies to check the cracks in concrete [53], the moisture content in concrete [54], and other applications [55, 56]. The same technology could be used in future studies.

4. Conclusions

Basing on the outcomes of this study, it can be reported some points and as follows:

1. The partial replacements of OPC with CKD and SF in mortars decreases the pulse velocity values when an increase in percentage. However, for small ratios of replacement, the durability of specimens shows a slight improvement.
2. Increase the curing period leads to obtain higher values of pulse velocity values when the cement is replaced by additional material in the mix.
3. Using 20 – 30 % as partial replacement of cement could be acceptable values, where increase this value leads to a slight increase in pulse velocity values of the mortar.

Additionally, the applied method in this study was the UPV, which could be categorized as a traditional method, therefore; more advanced methods are recommended to check the properties of mechanical properties of concrete, such as microwave sensors.

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