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Utilization of locally produced waste in the production of sustainable mortar

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ABSTRACT

Environmental pollution due to CO_2 emissions from the cement industry and the depletion of the natural resources of the aggregate used in the concrete industry call for the need to find alternatives to reduce these harmful effects. Some of these alternatives include the use of supplementary cementitious materials and the reuse of wastes from other industries as cement and aggregate replacement materials. Thus, this study was conducted to investigate the possibility of using autoclaved aerated (cellular) concrete blocks waste powder (CCP) that is locally produced as a partial substitute for cement or sand in mortar. Seven mixtures were cast. Three of them made by the substitution of the cement with CCP passed from 0.075 mm sieve (5%, 10 % and 15 % by weight), and other three mixtures comprised the replacement of natural sand with CCP of size 0.15−0.075 mm (5%, 10 % and 20 % by weight). A reference mixture (without replacement) was also performed for comparison purposes. The mechanical and water absorption properties were examined. Results indicated that among all tests examined, a sustainable mortar was produced by the substitution of the cement or sand with 10% CCP with an enhancement in the compressive strength without significantly affecting other properties of the mortar.

1. Introduction

Concrete is the main composite material used in the construction sector. The main concrete compounds are cement, fine and coarse aggregate, water and chemical admixtures [1]. The manufacturing of cement is associated with high CO_2 emissions and depletion of raw materials [2]. About 7% of CO_2 emission worldwide comes from the cement industry [3]. Furthermore, the extensive usage of natural aggregate in concrete manufacturing is one of the main reasons for its shortage in numerous countries worldwide [4]. Thus, in order to reduce the depletion of natural resources as well as the environmental damages caused by the cement industry, alternatives to cement and aggregates are needed in concrete production.

Furthermore, construction wastes are non-biodegradable and their disposal is expensive [5]. Consequently, one of the main troubles posing a universal challenge with the significant population growth is the recycling of solid wastes [6]. One of

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the smart endeavors is to reuse waste materials in other applications and convert them into valuable renewable materials [7]. Therefore, the introduction of these solid wastes into the construction industry as a substitute for cement or aggregates is thought to be a useful solution [8]. The use of waste materials as substitution of sand or cement has been studied extensively in the literature [9–11].

On the other hand, the aerated concrete which is also called cellular concrete is a lightweight concrete-type [12,13]. Autoclaved aerated concrete is a mixture of cement, water, fine aggregates and aluminum powder [14]. There are two methods for the production of cellular concrete either by autoclaved aerated concrete using an expansion agent or by adding foaming agent without autoclaving [15]. Limited studies dealt with the use of cellular concrete waste powder in concrete production. For example, Gyurkó et al. [16] studied the effect of using cellular concrete powders (CCP) as cement replacement (10 % by cement weight) on compressive strength and freezing-thawing resistance of concrete. The CCP is collected from the cutting process of cellular concrete blocks to the required size. Compressive strength results showed that the CCP increased the compressive strength by 34 %. Abed and Nemes [17] studied the influence of using collected CCP (in proportions of 15 % and 30 %) on the mechanical properties of the recycled aggregate self-compacting high strength concrete (SCHSC). Results indicated that the CCP reduced the mechanical properties (compressive, flexural and splitting tensile strengths) of the SCHSC as compared with the reference mix. Thus, the authors recommended using CCP at a percentage of less than 15 %.

Moreover, in Iraq, after 2003, as a result of the military actions, many buildings were destroyed in addition to the spread of poverty in some cities. As a result, some random neighborhoods were created by some low-income people, and these neighborhoods were mostly constructed by normal-weight concrete blocks as well as autoclaved aerated (cellular) concrete blocks (locally known as Thermo-stone) because of their availability locally and being inexpensive. With the improvement of the financial situation of these families in the following years, these houses were demolished, and consequently, large quantities of wastes resulted from this. Therefore, the management of these wastes, including cellular concrete blocks wastes, is an important problem. It is believed that one of the worthwhile solutions to reduce the negative impact of these wastes is by including them in the concrete industry.

According to the above literature, limited studies have been conducted to reuse CCP in the production of concrete or mortar and to study its effect on various concrete properties. Also, most of these studies used CCP produced during the process of cutting the cellular blocks and not that resulted from the crushing and grinding of the cellular concrete blocks. In addition, according to the authors' information, there are no or very limited studies in Iraq used cellular concrete blocks powder wastes as a substitute for cement or sand. Therefore, the novelty of this study is the recycling of locally produced waste and its reuse as a partial alternative to cement or fine aggregate. Moreover, the source of the powder in this study is the result of crushing and grinding of the cellular concrete blocks used in buildings and not the results of cutting the large blocks to small sizes in the factory as reported in previous researches. Thus, in order to reduce the environmental impact and enhance the sustainable development, this study was performed to investigate the potential use of CCP resulted from the crushing and grinding of locally produced broken cellular concrete blocks as a partial replacement of cement or fine aggregate in cement mortar. Accordingly, this study attempts to attain the following goals: investigating the effect of replacing the cement or sand partially by CCP on different properties of mortar. Additionally, orientating the disposal route of such waste from landfills to reuse in the concrete industry. Furthermore, replacing the cement or sand partially by CCP can aid in reducing the CO_2 emissions and consumption of natural resources that can contribute to sustainable development and support the low carbon circular economy of the construction materials.

2. Materials and methods

2.1. Materials used

2.1.1. Cement

Sulfate-resistant cement (Type, CEM I 42.5R-SR) was utilized in this study. The chemical composition of this cement (see Table 1) is identical to Iraqi Standard No. 5 / 1984 [18]. The specific gravity of this cement is 3.1 and the fineness (which is measured using Bettersize2000 laser particle size analyzer device) is 291 m^2/Kg. The particle size distribution of cement is presented in Fig. 1. Scanning electron microscope (SEM) image of cement is illustrated in Fig. 2.

2.1.2. Fine aggregates

Locally available natural sand was used as a fine aggregate. The grading of this sand is in accordance with Iraqi specifications No. 45 / 1980, first zone [19] as shown in Table 2. The fineness modulus, bulk density, specific gravity and water absorption of the fine aggregate are 2.718 Kg/m^3, 1570 Kg/m^3, 2.6 and 1.21 % respectively.

2.1.3. Cellular concrete powder (CCP)

The residue of the cellular concrete (autoclaved aerated concrete) powder, see Fig. 3, was used at different percentages as an alternative to cement or fine aggregate (sand) to explore its influence on different properties of mortar. The chemical composition of CCP is presented in Table 3. According to Asakura et al. [20] work, the dewatering of the bound water in a mortar powder (obtained from crushed concrete) increased the loss on ignition (LoI) value. Thus, the high LoI value of CCP that can be seen in Table 3 can be attributed to the dewatering of the bound water contained in the autoclaved aerated concrete powder. The cellular concrete blocks were broken and then ground by an electrical mill to turn them into a fine powder. The powder with a size passed through 0.075 mm

Table 1
The chemical compositions of cement.

Oxides	Content, %
CaO	61.2
SiO_2	22.4
Al_2O_3	3.3
Fe_2O_3	3.5
MgO	4.8
SO_3	1.81
Loss on ignition (LoI %)	2
Lime saturation factor (LSF)	0.86
Insoluble residue	0.99

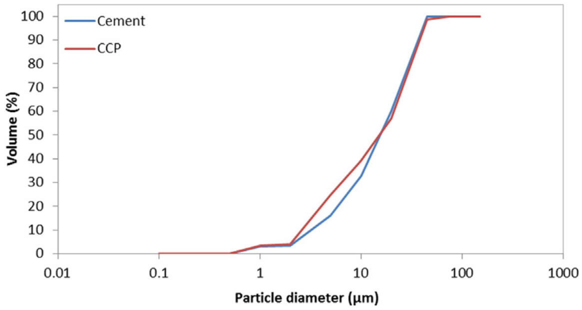

Fig. 1. The particle size distribution of cement and CCP.

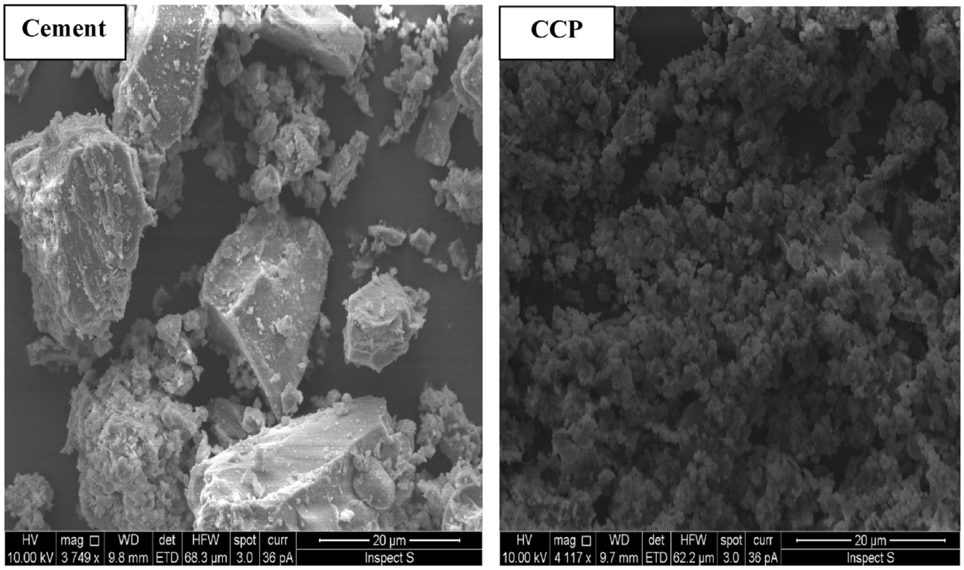

Fig. 2. SEM images of cement and CCP (dry powder).

sieve opening was used as a partial replacement of cement [21] while the powder with a size range of (0.15- 0.075 mm) was used as a substitute for natural sand. The specific gravity of CCP is 2.19. The fineness of CCP is 334 m^2/Kg. The particle size distribution of CCP is shown in Fig. 1 while its morphology (using SEM) can be seen in Fig. 2.

2.1.4. Superplasticizer

The third-generation superplasticizer purchased from BASF Company was used as a workability enhancer. This superplasticizer is conforming to ASTM C494 Type A & F [22].

2.1.5. Water

Tap water with an average pH value of 7.5 was employed for mixing all mortar mixtures.

Table 2
The grading of the fine aggregate (sand).

Sieve opening (mm)	Cumulative passing (%)	Iraqi specifications, grading (%)
4.75	96	90–100
2.36	83	60–100
1.18	53	30–70
0.60	33	15–34
0.3	6.2	5–20
0.15	0.6	0–10

Fig. 3. The cellular concrete powder (CCP).

Table 3
The chemical composition of cellular concrete powder.

Oxides	Content, %
CaO	21.9
SiO_2	54.3
Al_2O_3	6.1
Fe_2O_3	2.3
MgO	1.3
SO_3	4.7
Loss on ignition (LoI%)	9.3

2.2. Mix proportions

Seven mixtures were cast in this research: one control mix (without replacement), three mixtures include replacing the cement (by weight) with CCP passing through 0.075 mm sieve (5%, 10 %, 15 %) and the other three mixtures in which the sand was replaced with CCP (0.075–0.15 mm in size) in three proportions (5%, 10 %, and 20 % by weight). The mortar mixing ratios (by weight) adopted for all mixtures were 1:2.75 (binder materials: sand) and the water to cement ratio was 0.485. The granular size range of CCP used as a cement substitute (<0.075 mm) differs from that used as a sand replacement (0.15–0.075 mm), so the same substitution ratios were not used for either case. In addition, the amount of sand relative to cement that used in this study was 2.75, therefore in order to use as large as possible amount of CCP (toward sustainable development) as sand substitution material, the replacement rate has been raised to 20 % rather than 15 % as that for cement. In addition to what was previously mentioned, which is that CCP used as a substitute for sand is coarser than that used as a substitute for cement, and therefore both substitutions are independent of the other. Therefore, different replacement percentages were chosen for sand (5, 10 and 20 %) than those used for cement (5, 10 and 15 %). A similar substitution method was adopted in many previous works [23,24] where the replacement ratios were different for sand and cement (for the same material used) and the replacement level for sand was higher than that for cement. The superplasticizer was added for all mixtures in a fixed percentage (1.13% of binder materials weight). Details of mortar mixtures are displayed in Table 4.

2.3. Mixing procedure

A planetary mixer was used for mixing mortar constituents. The mixing process started by mixing the dry materials for 1 min at a speed rate of 140 rpm. After that, the water and superplasticizer, which were premixed together, were added and mixed at the same speed rate for an additional 1 min. Thereafter, the mixer was turned off for 0.5 min. Finally, all constituents were mixed at a speed rate of 285 rpm for 2 min.

2.4. Mold preparations, casting, consolidating and curing

Standard molds were prepared by cleaning and lubricating them with oil. The fresh mortar was cast into the standard molds after completion of the mixing process. The mortars were placed in $40 \times 40 \times 160$ mm^3 prisms and 50 mm^3 cubes in two layers and each layer was consolidated using vibrator. After 20–24 hrs. of casting, the molds were taken out and all the specimens were placed in water tanks and cured at room temperature for 28 days.

2.5. Program of testing

Several tests have been carried out in this study as shown in the following sections:

2.5.1. Fresh tests

2.5.1.1. Flow rate. After end of mixing, the flow rate of the fresh mortars was measured utilizing the flow table method in accordance with ASTM C1437 [25].

2.5.2. Hardened tests

2.5.2.1. Compressive strength. Prism specimens ($40 \times 40 \times 160$ mm^3) were used for compressive strength testing. The parts of these prisms, which were broken into two halves in the flexural test machine, were used to complete this test. One testing age (28-days), an average of six readings for each result were adopted.

2.5.2.2. Water absorption. The water absorption test was executed using the method described in ASTM C642 [26] at 28 days. Three cubes (50 mm^3) were cast for each mixture.

2.5.2.3. Bulk density. The bulk density test was performed at 28 days using the 50 mm^3 cubes where the cubes were weighed and their actual dimensions were measured. Then by dividing the weight of each cube by its dimensions, the bulk density was determined. Three readings were adopted for each result and average of three cubes was used to represent the result.

2.5.2.4. Ultrasonic pulse velocity (UPV). The UPV (non-destructive test) was examined using mortar cubes, see Fig. 4. The test involves measuring the time of the wave (in microseconds) transmitted through the material and then the speed of the wave is extracted by dividing the distance traveled on the measured time. The same cubes used to measure the water absorption rate were used for this test. After extraction from water (after the end of curing) and before the examination of water absorption, the UPV test was performed. Where, after removing the specimens from water curing, immediately, the excess water was removed from their surface then the UPV readings were measured. Thereafter, the specimens were oven-dried for water absorption test. Thus, the drying process of specimens was not conducted until all of the UPV measurements have been completed. An average of three readings was adopted for each mixture.

Table 4
Details of mortar mixtures (Kg/m^3).

Mix designation	Cement	Sand	Cellular concrete powder		Water	Super- plasticizer (% of the binder)
			< 0.075 mm	0.075–0.15 mm		
M0	587	1614	0	0	285	6.63 (1.13)
MC5	558	1614	29	0		
MC10	528	1614	59	0		
MC15	499	1614	88	0		
MS5	587	1533.3	0	80.7		
MS10	587	1452.6	0	161.4		
MS20	587	1371.9	0	242.1		

Fig. 4. The ultrasonic pulse velocity test of mortar cubes.

3. Results and discussions

3.1. Flow rate

The flow rate results of mortar mixtures are shown in Fig. 5. The flow rate values were ranged between 142 to 240 mm. The results for mixtures containing CCP as a substitution of cement showed that the flow rate increased by 8% and 1% for replacement ratios 5% and 10 %, respectively, while replacing the cement with 15 % CCP reduced the flow rate by 1% related to the control mixture. The increased flow rate at 5% CCP compared to the control and other mixtures (MC10 and MC15) could be attributed to the particle packing enhancement of mortar at this replacement level, which led to reduce the water demand and improve the flowability [27,28]. The higher specific surface area of CCP (334 m^2/kg) compared to that for cement (291 m^2/kg) supports this claim. On the other hand, the slight reduction in the flow rate of mixture incorporated higher CCP content (MC15) relative to the control mixture could be attributed to the high void spaces that illustrated the high water demand of CCP as can be seen from the SEM image of the CCP in Fig. 3 [29,30].

For mixtures with CCP as a sand replacement, the flow rate increased by 4% at the 5% replacement level. However, the flow rate was reduced steadily with higher replacement levels by about 13 % and 36 % for MS10 and MS20 mixtures, respectively. This reduction could be due to the high absorption capacity of CCP grains [17]. This reduction in the flow rate was more pronounced in the high replacement levels. In addition, the reduction was more pronounced in samples incorporated CCP as sand replacement relative to that of the cement replacement mixtures. This is owing to the higher water demand of fresh mortars as a result of replacing the sand with a finer material [31]. The results also showed that the reduction rate in the flow increased as the percentage of replacement in both replacement types (cement or sand) arose.

3.2. Compressive strength

The compressive strength results for the reference and CCP mixtures are shown in Fig. 6. The compressive strength values of mortars were within the range of 30.3–58.5 MPa. It is clear from Fig. 6 that if the cement was compensated with the CCP, the compressive strength was improved by 6% and 5% for MC5 and MC10 mixtures, respectively, while the strength was

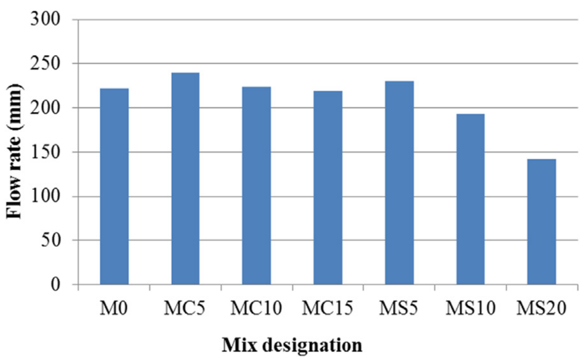

Fig. 5. Flow rate results of mortar mixtures at 28-day.

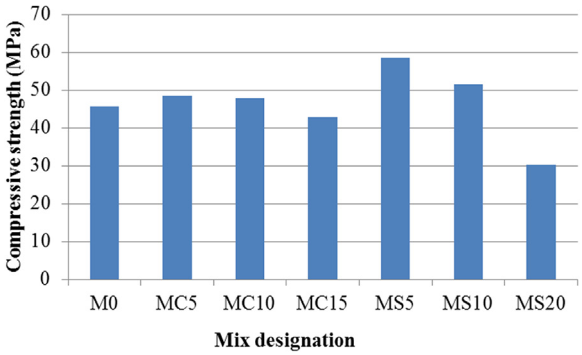

Fig. 6. Compressive strength results of mortars at 28 days.

decreased by 6% for MC15 mixture. Moreover, according to the results of the previous works [17] as well as in the current investigation, it seems that the filling effect is the major role of CCP in mortar (weak pozzolanic activity). The results of the chemical analysis of CCP can clarify this matter. Where, according to ASTM C618 [32], one of the main chemical requirements for a material to be considered as a pozzolanic material is the sum of Al_2O_3, Fe_2O_3 and SiO_2 which must be equal or more than 70 %. For CCP, the sum of these oxides was less than 65 %. For sand replacement mixtures, there was a significant boost in compressive strength for replacement ratios of 5% and 10 % where the compressive strength was improved by 28 % and 13 %, respectively. On the other hand, the 20 % replacement ratio caused a reduction in the compressive strength by 34 % in relation to the CCP-free mixture. Moreover, the results demonstrated that the compressive strength decreased with increasing the replacement ratios for both replacements (cement and sand). It can be concluded from the results of cement and sand substitutions that the CCP presence had a favorable impact on compressive strength property up to the level of 10% replacement. This increase could be due to increasing the filler effect of CCP in the hardened mortar [33]. Beyond that, the compressive strength was decreased. The reduction in the compressive strength for mixtures incorporated CCP as replacement to cement could be imputed to the higher replacement of cement with a low activity material [34] as well as to the dilution effect of C_3S and C_2S [35–37]. Additionally, the reduction in compressive strength for mixtures with CCP as sand replacement at high replacement ratios is owing to the loss in packing density where the fine particles of CCP and sand pressed each other's and reduced packing [38–40].

3.3. Water absorption

The water absorption results of mortars are displayed in Fig. 7. The results indicated that all mortars incorporated CCP as a substitution for cement or sand showed a higher absorption rate than the control sample except MC5, which showed equal absorption to that of the reference mixture. Regardless of the type of substitution, the increase in water absorption was increased by increasing the content of CCP in the mixture. The maximum absorption rates for cement and sand replacement mixtures were 8.5 % (for MC15 mix) and 11.7 % (for MS20), respectively compared to 7.7 % for the reference mixture. This increase in absorption rates for most mixtures can be explained according to Wongkeo et al. [41], who reported that a direct relationship between the voids in the matrix and the water absorption was recorded. Other meanings, the higher the voids percentages, the higher is the absorption rate. This claim is supported by the UPV results of this study. Moreover, the significant increase in water absorption of MS20 mixture could be attributed to its lower flow rate value compared to all other mixtures. Where Özcan and Koç [42] reported that the reduction in workability leads the concrete to trap a large

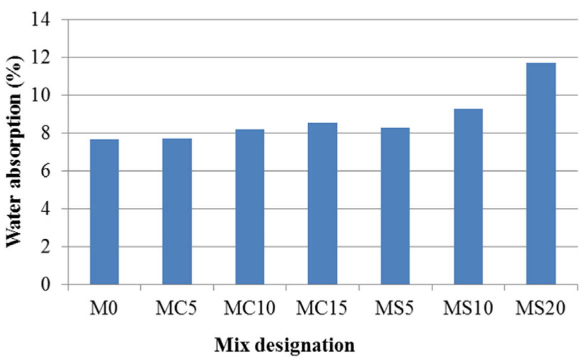

Fig. 7. Water absorption results of mortars at 28 days.

quantity of air. Accordingly, a high amount of water would be absorbed. However, the absorption rates for all mixtures except for MS20 were less than 10% by mass which mean good quality mortars were produced [43,44].

Moreover, when comparing the results of water absorption with those obtained in the compressive strength test, a mismatch is observed in some mixtures. This can be explained according to Zhang and Zong [45] and Dean [46] who reported that there is no direct relationship between the compressive strength and water absorption.

3.4. Bulk density

The bulk density results of mortars are presented in Fig. 8. The bulk density of the hardened mortar or concrete is governed by many parameters, such as the entrapped or entrained air voids, the amount and density of aggregate as well as the cement and water content [41,47]. The results of the present study showed that cement substitution mixtures reduced the density by 3% except for the MC5 mix, where the density was similar to that for the reference mixture. Moreover, it was observed from Fig. 8 that the higher the replacement level, the lower was the bulk density which can be referred to the excess of water/cement ratio (due to cement reduction) that led to increase mortars porosity [48].

For sand replacement mixtures, the density was reduced by 1%, 4% and 9% for MS5, MS10, and MS20 mixtures, respectively. As is obvious in sand replacement mixtures, the density is constantly decreasing as the replacement ratio increases. This may be due to the reduction of the plasticity of the mixtures (as found in the flow rate results), which makes the entrapped air in the fresh mixture difficult to escape and thus reduce the density of the hardened mortar.

Moreover, the lower specific gravity of CCP (2.19) compared to cement (3.1) and sand (2.6) had also a significant effect in reducing the hardened density of mortars. This effect was more pronounced in higher substitution levels (more than 5%) of CCP with the cement or sand.

3.5. UPV

The UPV can be used to assess the presence of voids, concrete quality, effectiveness of cracks repairs [49] as well as concrete durability [50]. The UPV results are presented in Fig. 9. The results showed that the UPV values of mortar mixtures were ranged from 3722 to 4144 m/s. According to Mohseni et al. [51], these values indicate that the produced mortars containing CCP had good durability, as they stated that if the velocity values are within the range 3660–4575 m/s, they have good durability.

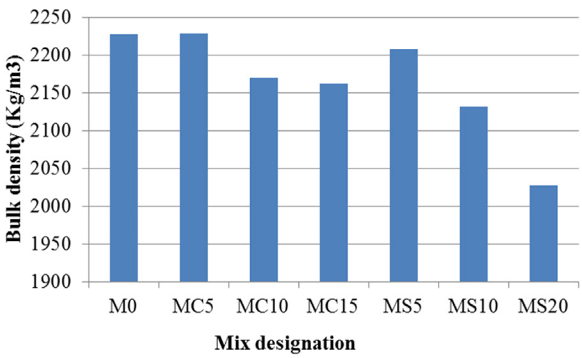

Fig. 8. Bulk density results of mortars at 28 days.

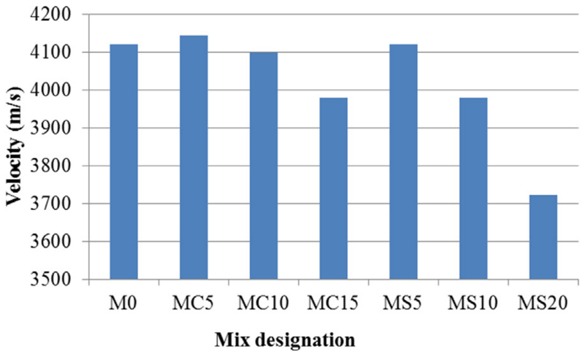

Fig. 9. UPV results of mortar mixtures at 28-day.

For cement replacement mixtures, the results showed that the velocity was improved by about 1% for the MC5 mixture while it was reduced by 1% and 3% for MC10 and MC15 mixtures, respectively. Other meanings, the UPV was decreased as the replacement ratio was increased. Moreover, it was noted that the UPV and compressive strength had a similar trend. This behavior can be explained according to Awoyera et al. [52] who reported that the ultrasonic travel time is influenced by the cemented materials compactness.

For sand replacement mixtures, the MS5 mix showed a velocity value equal to that for the reference mixture, while the velocity was reduced by 3% and 10% for MS10 and MS20 mixtures, respectively. As in the case of cement substitution mixtures, the velocity was reduced by increasing the content of the CCP in the mixture. The reason for this behavior is due to the increase in the percentage of air spaces in the mixture as the CCP increased, as confirmed in the results of density and water absorption tests in this study.

4. Conclusions

Considering the results acquired in this study, the following are concluded:

1 The flow rate of mortars improved with the incorporation of up to 5% CCP as sand replacement and up to 10 % CCP as cement replacement material.
2 The compressive strength of the hardened mortar improved with the utilization of up to 10 % CCP as cement or sand replacement with a maximum compressive strength achieved at 5% CCP for both types of substitutions. After that, the compressive strength decreased.
3 Replacing the cement or sand with CCP resulted in reduced bulk density and UPV of mortars except for the MC5 mix, where the density was equal to the reference mixture and the velocity was improved by about 1%.
4 Using CCP increases the water absorption of mortars except for MC5 mixture, where it showed equal absorption rate to that of the reference mixture. However, the absorption rates for all mixtures except MS20 were less than 10%, which indicate good quality mortars were produced.
5 The best performance was recorded for mortar containing 5% CCP as cement replacement with an improving (or similar results) in the fresh, mechanical and durability properties. However, from an environmental viewpoint, the 10% CCP by weight of cement considered satisfactory for all properties performed in this investigation as was considered as the optimum replacement level in this study.

Declaration of Competing Interest

The authors report no declarations of interest.

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