Fresh Behavior and Hardened Properties of Self-Compacting Concrete Containing Coal Ash and Fly Ash as Partial Replacement of Cement

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Abstract. Due to the higher price of cement compared to other concrete ingredients, the problems associated with greenhouse gases emissions during its production and its high popularity have arisen concerns in its substitution with other supplementary cementitious materials (SCMs). In this regard, the current experimental program was established to investigate the fresh and hardened performance of self-compacting concrete (SCC) made with coal ash (CA) and fly ash (FA) as fractional substitution of cement. In this paper an attempt was made to use the remaining CA from the barbecue process of the restaurants from Fallujah city, Iraq. A total number of 7 concrete mixes were prepared with unchanged (w/b) ratio of 0.37 and total cementitious content of 450 kg/m³. Reference mix was produced by using 100% cement without FA or CA. Then, other mixtures were batched with 10%, 20% and 30% (by weight) replacement of cement by FA and CA, respectively. The results illustrated that, in contrast to the FA, the CA has negative influences on the fresh properties of SCC but the results still meet the criteria for the fresh behavior of SCC. On the other hand, the inclusion of CA was significantly improved the strength and water absorption of SCC. Sustainable high strength SCC can be produced due to the addition of CA.

Keywords: Self-compacting concrete; Coal ash; Fly ash; Fresh properties; Hardened properties
1. Introduction

Due to the high demand for cement as the main construction material, its higher prices compared to other concrete constituents and the problems associated with emissions of greenhouse gases during its production made a huge interest to replace them with pozzolanic materials such as SCMs. As mineral admixtures, there have been numerous waste materials used in concrete to protect the environment. However, by using pozzolanic mineral admixtures, mechanical properties and the stability of the concrete have been improved. Besides, they can also be utilized as a way for decreasing the consumption of cement and the emission of carbon dioxide which causes global warming and waste of raw materials. The term green concrete can be used for these types of concretes (Golewski, 2018).

In the previous studies, a huge amount of investigations can be found regarding the incorporation of different pozzolanic materials into the concrete to partially replace Portland cement (Al-Jumaily et al. 2015), the materials used include FA (Güneyisi et al. 2016; Al-Hadithi, & Hilal, 2016; Adak et al. 2017; Faraj et al. 2020), silica fume (Mastali & Dalvand, 2018; Faraj et al. 2019), rice husk ash (Chakraborty & Goswami, 2015; Ahsan & Hossain, 2018), palm oil fuel ash (Mujah, 2016; Zeyad et al. 2016), coconut shell ash (Oyedepo, 2015), shell sunflower ash and shell pumpkin ash (Shahbazpanahi & Faraj, 2020).

From the chemical point of view, the pozzolan materials are siliceous or siliceous-aluminous. They have little inherent cementitious value alone, while during their reaction with saturated calcium hydroxide (C-H) extra calcium silicate hydrate (C-S-H) is produced. Thus, calcium silicate and calcium hydroxide represents the major products of cement hydration (Omrane et al. 2017). Therefore, the pozzolanic materials can have the ability to form additional C-S-H during hydration by which the matrix can be improved. The pozzolanic reactivity of mineral admixtures can significantly impact the strength and durability of concrete. Burning and grinding of waste materials are the best ways to produce pozzolan materials (Shahbazpanahi & Faraj, 2020).

SCC can be regarded as high performance and special concrete type because it can be poured and vibrated inside any form shapes due to its self-weight without any outside efforts, also it assures total filling of forms even when the reinforcement with little spacings are present. Therefore, the cohesiveness along with the flowability of fresh concrete is highly crucial for SCC (Güneyisi & Gesoğlu, 2008). On the other hand, SCC is generally produced by lower w/b ratio and higher cement quantity is required compared to the traditional concrete. Thus, a higher amount of binders such as FA, lime dust, silica fume, and GGBFS can be used as a substitute of cement in order to prevent dissimilar dispersion of larger particles in the fresh concrete. Also, the flowability, passing ability, and stability of SCC can be enhanced due to the addition of viscosity modifying and superplasticizer admixtures, but the total cost of the produced concrete is amplified (Güneyisi et al. 2015; Kurt et al. 2016).

The expenditure of SCC usage can be decreased with the inclusion of mineral admixtures. Moreover, to develop the workability and slump of concrete mixes, generally mineral admixtures such as FA, limestone filler and GGBFS can be easily quantified (Faraj et al. 2020). It is noted that FA, among these materials, enables to enhance the mechanical and resilience features of concrete when it replaces cementitious materials. The inclusion of FA also allows decreasing the need for chemical admixtures to control the viscosity level (Bilodeau et al. 1994).

Global concerns are raised to decrease the consumption of natural resources in concrete production and replace them with alternative waste materials. Therefore, the main aim of this study is to develop sustainable high strength SCC by reducing the cement content through its replacement with mineral waste materials such as FA and CA.

2. Research significance

Due to a high number of restaurants especially in the tourist places and in the city centers a large amount of remaining coal ash (CA) from the barbecue process is generated. This ash can be regarded as waste material and may be hazardous to the environment. Thus, in this paper an attempt was made to use the remaining CA from the barbecue process of the restaurants from Fallujah city, Iraq, which their number is more than 20 restaurants. The researches regarding the influence of the CA on the performance of SCC is limited. Therefore, this article mainly aims to make a comparison between the effects of CA and
FA as a partial replacement of cement on the fresh and some hardened features of SCC.

3. Experimental program

3.1 Materials

The main material which has been used as a cementitious material in this study was Ordinary Portland cement from Al-MASS Company. While the supplementary cementitious materials used for partially replacing the cement were Class F FA and CA. The chemical composition of CA, FA, and cement are shown in Table 1. Moreover, the physical characteristics of cement are reported in Table 2. Also, figure 1 demonstrates both SEM images analysis of FA and CA respectively. The CA powder which was obtained from different restaurants was sieved through sieve 75 µm. The Grading and physical properties of used coarse aggregate and natural river sand utilized in this study are given in Table 3 and Table 4, respectively. Thus, for the sake of accomplishing the required workability of SCCs, a high-performance superplasticizer known commercially as (ViscoCrete - 5930) was used with a specific gravity of (1.08).

Table 1. Chemical compositions of PC, FA and CA

| Chemical analysis (%) | PC | FA | CA |
|-----------------------|----|----|----|
| SiO₂                  | 20.9 | 68.67 | 2.098 |
| CaO                   | 63.22 | 1.926 | 31.29 |
| Fe₂O₃                 | 3.85 | 1.725 | 0.807 |
| Al₂O₃                 | 4.89 | 0.43 | 0.159 |
| MgO                   | 2.82 | 2.49 | 4.37 |
| SO₃                   | 2.73 | 0.758 | 5.454 |
| K₂O                   | 0.92 | 2.488 | 4.77 |
| Na₂O                  | 0.22 | - | - |
| P₂O₅                  | - | 0.69 | 2.406 |

Table 2. Physical properties of cement used in the mixtures

| Test type                               | Specification (the Iraqi standard No.5/1984) | Cement used |
|-----------------------------------------|--------------------------------------------|-------------|
| Fineness by Blain air permeability apparatus (cm²/gr) | ≥ 2300 | 2500 |
| Initial setting (min.)                  | ≥ 45 | 130 |
| Final setting (min.)                    | ≤ 600 | 250 |
| Soundness                               | ≤ 0.8 | 0.8 |
| Compressive strength                    |                |             |
| 7 days (MPa)                            | ≥ 23 | 27.5 |
| 28 days (MPa)                           | - | 32.9 |
Figure 1. SEM images of (a) FA and (b) CA

Table 3. Sieve analysis results and physical properties of coarse aggregate

| Sieve size (mm) | % Passing | % Passing (ASTM C33) |
|-----------------|-----------|----------------------|
| 12.5            | 100       | 100                  |
| 9.5             | 86.76     | 85-100               |
| 4.75            | 14.12     | 10-30                |
| 2.36            | 0.16      | 0-10                 |

| Physical Properties |
|---------------------|
| Specific gravity    | 2.7       |
| Water absorption    | 0.3%      |
| Maximum particle size | 10 mm   |

Table 4. Sieve analysis results and physical properties of fine aggregate (river sand)

| Sieve size (mm) | % Passing | % Passing (ASTM C33) |
|-----------------|-----------|----------------------|
| 4.75            | 100       | 95-100               |
| 2.36            | 85.1      | 80-100               |
| 1.18            | 70.5      | 50-85                |
| 0.6             | 58.86     | 25-60                |
| 0.3             | 28.41     | 5-30                 |
| 0.15            | 7.2       | 0-10                 |
| 0.075           | 1.9       | 0-3                  |

| Physical Properties |
|---------------------|
| Specific gravity    | 2.7       |
| Water absorption    | 0.8%      |
| Fineness modulus    | 2.5       |
3.2 Mix proportions

As a methodological procedure for evaluating the performance of SCC containing CA and comparing its effects with FA, an overall number of 7 SCC mixtures were designed with a constant (w/b) ratio of 0.37 and total binder content of 450 kg/m$^3$. The control mixture was produced by using 100% cement without FA or CA. Then, other mixtures were prepared with 10%, 20%, and 30% (by weight) replacement of cement by FA and CA, respectively. The mixture proportions of SCC are shown in Table 5.

Table 5. Mixture proportions (Kg) of SCC for 1 m$^3$ of concrete

| Mix ID | Cement | Sand | Gravel | Water | SP | FA | CA |
|--------|--------|------|--------|-------|----|----|----|
| C      | 450    | 915  | 885    | 170   | 8  | 0  | 0  |
| M1     | 405    | 915  | 885    | 170   | 8  | 45 | 0  |
| M2     | 360    | 915  | 885    | 170   | 8  | 90 | 0  |
| M3     | 315    | 915  | 885    | 170   | 8  | 135| 0  |
| M4     | 405    | 915  | 885    | 170   | 8  | 0  | 45 |
| M5     | 360    | 915  | 885    | 170   | 8  | 0  | 90 |
| M6     | 315    | 915  | 885    | 170   | 8  | 0  | 135|

3.3 Mixing procedure and Preparation of the samples

Mixing procedure is an actual significant stage in SCC production that depends on the quantity of elements comprising of binders, coarse and fine aggregates, furthermore the water and admixtures. The procedures set by EFNARC (2005) as a methodology for the production of SCC as well as the direct technique proposed by Kheder et al. (2010) were followed in this study. Mixtures of SCC were prepared by adding a small quantity of water with half of aggregates (sand + gravel) to the mixing pan. The mixer was rotated for 1 minute, then part of the cementitious materials (the cement or cement + FA or CA) was supplemented to the mixture plus partial amounts of sand. The mixture rotated for another 1 minute. Next, quantitatively, half of (water plus superplasticizer) that has been added to the mixture and the process of mixing were continued for about 2 minutes till materials became homogenous, finally remaining constituents including (sand and gravel, superplasticizer and water) added to the mixer. At this stage, the mixing was continued for an extra 3.0 minutes. Afterward mixing, the fresh SCC mixtures were tested for fresh behavior, then for each mixture nine cubic molds with sizes of 100*100*100 mm and three prism molds with a measurement of 500 *100*100 mm were cast for completing tests of compressive strength, density water absorption and flexural strength, respectively. The molds of SCC were enclosed with pieces of polyethylene for 1 day. Finally, the samples were de-molded and maintained in water at 20 C° temperature till the age of the tests.

3.4 Testing procedures

In this section, the procedure used to carry out the tests for fresh and hardened properties of SCC mixtures according to the related standards for each test is explained in detail.
3.4.1 Fresh properties

For measuring slump flow diameter (SFD) and the slump flow time (SFT), a cone with an ordinary slump flow was chosen, and then it was filled up with concrete without being leveled and compacted. After lifting the cone and the concrete is spread, the average diameters of the spread concrete have been subsequently measured as shown in Figure 2. As proposed by EFNARC (2005), three typical classes of slump flow have been regarded to identify the range of applications. The typical application areas and various boundaries lower and upper, of the different classes, are provided in Table 6. However, the test of slump flow was conducted and its time (T50), the determinant that identified the time in which the concrete reached the 500 mm spread circle, was also calculated. EFNARC suggests T50 of 2 to 5 seconds for SCC.

![Figure 2. Measurement of SFD and SFT for SCC mixtures according to EFNARC (2005).](image)

Figure 3 illustrates the process of evaluating the flowability and the viscosity of the mixture in which the experiment was accomplished. The determination of time has been done by using a simple methodology in which the funnel has been filled with a material of fresh concrete. Additionally, the time flow has been measured during the opening of the orifice until the funnel being drained completely. An adequate and stable concrete would have been consuming a short time for flowing out. Two kinds of viscosity classes in the EFNARC (2005) SCC guide according to the measured V-funnel time (VFT) and T50. Thus, the viscosity classification was also shown in Table 6.
Figure 3. Photographic view of VFT measurement of SCC mixtures according to EFNARC (2005).

The L-box equipment consisted of a rectangular-section box which resembled an L in shape, having horizontal and vertical parts, was used. The horizontal and vertical parts were separated by a movable gate in which vertical bars are fitted (Figure 4). The vertical part was filled out with concrete and subsequently the concrete flew into the horizontal part. After the gate has been lifted and the flow of the concrete being stopped, the height of the concrete settled in the horizontal part was regarded as the ratio of the concrete retained in the vertical section \( \frac{H_2}{H_1} \). It indicated the slope of the rest concrete. This procedure is deliberated on the passing ability or the degree by which evacuation of concrete via the bars is limited.

Figure 4. Photographic view of L-box apparatus used for the measurement of \( \frac{H_2}{H_1} \) ratio of SCC mixtures according to EFNARC (2005).
Table 6. Passing ability, slump flow and viscosity classes according to EFNARC (2005)

| Class | $T_{50}$ (seconds) | VFT (seconds) |
|-------|-------------------|---------------|
| Viscosity | | |
| VS1/VF1 | $\leq 2$ | $\leq 8$ |
| VS2/VF2 | $>2$ | 9-25 |
| Passing ability | | |
| PA1 | $\geq 0.8$ with two rebar | |
| PA2 | $\geq 0.8$ with three rebar | |
| Class | | SFT |
| Slump flow | | |
| SF1 | | 550-650 |
| SF2 | | 660-750 |
| SF3 | | 760-850 |

3.4.2 Hardened properties

As for the compression strength, the experiment of compressive strength has been accomplished by using a 100 mm cubes at the age of 7 and 28 days. This experiment was performed by using of 2000 KN hydraulic machine. The stress rate of compression has been measured in terms of dividing the maximum capacity load of the cubes by the face zone and the average of three cubes is reported (Standard, B 1983).

For determining the flexural strength of the specimens the three-point bending test was performed and the loading rate was designated to be 1.0 (N/mm$^2$/min) (ASTM, C78. 2010).

The water absorption test was conducted on the cube specimens following (ASTM, C642. 2008). The average of three cubes was reported for each mix.

The cube samples were also used to determine the dry density of the SCCs. The procedure was conducted according to (ASTM, C138. 1986)

4. Results and discussion

4.1 fresh properties

4.1.1 SFT and $T_{50}$ SFD

The SFT and $T_{50}$ results for SCC made with dissimilar dosages of FA and CA are shown in Figure 5 and Figure 6, respectively. It is noted from Figure 5 that as a result of increasing the FA content, the flowability of SCC has been increased too remarkably. Increasing FA content from 0% to 30% resulted in an increase of SFD from 700 mm to 770 mm. On the other hand, the addition of CA into the SCC resulted in the opposite behavior as it is compared to FA. The addition of 30% CA into the SCC reduced the SFD by about 14% compared to the control mixture. Moreover, the mixture that contains 30% FA has 22% higher SFD as compared to the mixture containing the same percentage of CA. Adding 30% FA shifted the mixture class from SF2 to SF3, while adding the same percentage of CA shifted the mixture class from SF2 to SF1. All produced mixtures containing either FA or CA satisfied the fresh
criteria for SCC proposed by EFNARC (2005), but the classes were remarkably different for mixtures made with FA or CA.

Regarding the time of slump flow, as it is shown in Figure 6, the addition of CA also increases the $T_{50}$ time, which means higher time is required for SCC to reach 500 mm diameter, thus the flowability decreased. However, the inclusion of FA slightly decreased $T_{50}$ times. The mixture containing 30% FA has 77% lower $T_{50}$ time compared to the same mixture but contained 30% CA.

![Figure 5. SFD of SCC mixtures containing different percentages of FA and CA](image)

![Figure 6. SFT of SCC mixtures containing different percentages of FA and CA](image)
4.1.2 V-funnel flow time

Figure 7 shows the VFT versus the partial replacement of FA and CA with cement. It is obvious from the results that the addition of CA significantly amplified the VFT, thus the filling ability of SCC has been decreased. Increasing the CA content from 0% to 30% amplified the VFT from 8 seconds to 17 seconds. In contrast, the addition of FA gradually decreased the VFT. The mixtures containing CA can be categorized as VF2, while the mixtures containing FA can be classified as VF1 according to EFNARC (2005).

On the other hand, the VFT versus T$_{50}$ flow time for SCC made with FA and CA as it is shown in Figure 8. This figure can be used to identify the viscosity classes of SCC. As can be seen from Figure 9 mixtures containing FA can be regarded as VS1/VF1 class whereas the mixture that contains CA should be regarded as VS2/VF2 class.

![Figure 7. VFT of SCC mixtures containing different percentages of FA and CA](image)

![Figure 8. VFT versus T$_{50}$ flow time of SCC mixtures containing different percentages of FA and CA](image)
4.1.3 L-box ratio

As for the passing ability of SCC in terms of the L-box height ratio, it was significantly reduced by amplifying the CA content as demonstrated in Figure 9. Moreover, contrasting other fresh properties the addition of FA also decreased the passing ability of SCC but with a small range compared to CA. The inclusion of 30% CA resulted in a 37% reduction in the L-box height ratio. The mixtures containing CA cannot meet the fresh criteria for SCC regarding the passing ability.

The overall fresh results illustrated that the CA involves a negative impact on the fresh behavior of SCC, but the majority of the results still meet the criteria required for the fresh behavior of SCC. The main reason behind decreasing the fresh properties with increasing the CA content is assigned to the fact that those particles of CA was in the nano-scale compared with particles of cement and FA which in the micro-scale, thus the CA particles have higher surface area and needs more quantity of water to wet all surface area of the particles (Shahbazpanahi & Faraj, 2020).

4.2 Hardened properties

4.2.1 Dry density

The dry density of SCC containing different percentages of FA and CA is presented in Figure 10. Mixtures with CA had higher dry density compared to those containing FA at all testing ages. The inclusion of CA leads to the surge of the dry density of SCC at 7 and 28 days. This may be accredited to the fact that, because the CA particles had greater surface area when compared with cement and FA particles, thus during the hydration process more water was converted to the hydration products, made the micro structure less porous, more packed and increased the density of the produced concrete. The mixture containing 20% FA had a dry density of about 7% and 9.5% lower than that containing the same percentage of CA at 7 and 28 days, respectively.
4.2.2 Compression strength

The compressive strength of SCC has remarkably been increased with increasing CA content up to 20% at 7 and 28 days, as shown in Figure 11. Nevertheless, this behavior was different for SCC containing FA. The compressive strength was decreased with the inclusion of 10% FA, and then it was increased with the addition of 20% and 30% of FA at both testing ages. The mixtures containing 10% and 20% of CA and 30% of FA might be considered as self-compacting high strength concrete (SCHSC), because the strengths higher than 60 MPa were obtained at 28 days (Faraj et al. 2019; ACI 363R-10). The compressive strength of SCC was increased by about 30% and 46% with the inclusion of 20% and 30% of CA and FA, respectively. Increasing the compressive strength with the addition of CA can be assigned to the highly lower diameters and higher surface area of the particles that enhanced the ITZ and microstructure of the matrix (Al-Jumaily et al. 2015). The results also demonstrated that the compression failure mode of SCC mixtures containing FA were more brittle than the reference mixture and mixtures made with CA as shown in Figure 12.

Figure 10. Dry density of SCC mixtures containing different percentages of FA and CA

Figure 11. Compressive strength of SCC mixtures containing different percentages of FA and CA at 7
Figure 12. Compression failure mode of different samples at 28 days (a) reference SCC mixture (b) Mixture containing 10% FA, and (c) Mixture contains 10% CA.

4.2.3 Flexural strength

The flexural strength of SCC containing various percentages of FA and CA at 28 days is illustrated in Figure 13. The flexure failure mode of the different SCC mixtures is also presented in Figure 14. It is obvious from the findings that the flexural strength of SCCs involving different percentages of FA and CA were lower than the control sample. However, the lowest flexural strength of SCC was achieved for the mixture containing 10% FA which was 46% lower than that of the control mixture. On the other hand, the highest flexural strength was gained for the mixture that contains 30% CA which was about 8% higher than the reference sample. Moreover, the mixtures containing CA had a higher flexural strength of the mixes containing FA, because the microstructure of the matrix and ITZ was better improved with the addition of CA compared to the FA.

Figure 13. Flexural strength of SCC mixtures containing different percentages of FA and CA at 28 days
Figure 14. Flexure failure mode of different samples at 28 days (a) reference SCC mixture (b) Mixture containing 10% FA, and (c) Mixture contains 10% CA.

4.2.4 Absorption

The water absorption test results of SCC comprising different percentages of FA and CA are shown in Figure 15. Generally, the water absorption of SCC was remarkably decreased with the inclusion of FA and CA. The positive impact of CA on the water absorption was more obvious especially at a 30% replacement level compared to FA. The water absorption of SCC was reduced by about 29% and 58% by the addition of 30% FA and 30% CA, respectively. A main reason behind decreasing the water absorption of SCC is that, due to the pozzolanic reaction of FA and CA the microstructure of the matrix was significantly improved (Faraj et al. 2020). Moreover, the CA particles were much smaller than cement particles, thus during hydration the compactness of the hydrated structure was considerably enhanced, which resulted in the disconnected pore structure of the matrix.

Figure 15. Water absorption ratio of SCC mixtures containing different percentages of FA and CA
5. Conclusions
According to the outcomes reached through this study, some conclusions can be drawn:

1. The waste material resulted from the barbecue process was obtained and used as a partial replacement with cement to produce sustainable SCC. Moreover, the influence of CA on the SCC fresh as well as the hardened properties was studied and compared with the FA effects.

2. Generally, the fresh behavior of SCC has been negatively impacted by the CA but the majority of the results still meet the criteria required for the fresh behavior of SCC.

3. The fresh properties of SCC have been improved by the FA addition in terms of flowability, filling ability, and passing ability.

4. The dry density of SCC has been increased along with the increase of CA content starting from 0% to 30% and it was reduced with increasing the FA content.

5. There has been a significant enhancement in the compressive strength of SCC that has been significantly improved when the CA content up increased to 20% and then decreased with a further increase of the CA content.

6. The CA can be regarded as a significant pozzolanic material for producing SCHSC with compressive strength higher than 60 MPa.

7. Both CA and FA involve a negative effect on the flexural strength of SCC at 28 days, but it’s worth mentioning that the influence of CA has been insignificant compared to the effect of FA.

8. The water absorption of SCC was increased gradually by raising the (CA) content, and it was also dramatically amplified with the addition of FA.

Abbreviations and definitions
- CA: coal ash
- C-H: calcium hydroxide
- C-S-H: calcium silicate hydrate
- EFNARC: European Federation of National Associations Representing for Concrete
- FA: fly ash
- GGBFS: ground granulated blast furnace slag
- LHR: L-box height ratio
- PC: Portland cement
- SEM: scanning electron microscopy
- SCC: self-compacting concrete
- SCHSC: self-compacting high strength concrete
- SCM: supplementary cementitious materials
- SFD: slump flow diameter
- SFT: slump flow time
- SP: superplasticizer
- VFT: V-Funnel flow time
- W/b: water/binder
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