Impact resistance and mechanical properties of High Strength Concrete containing local material

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Abstract
High Strength Concrete (HSC) is an expression which is used to define a concrete with high performance and strength exceeds 40 MPa. The high elasticity or strength and low shrinkage and permeability are considered the main properties of the HSC. The aim of this study is to investigate the effect of High Reactivity Metakaolin (HRM) and/or Silica Fume (SF) on the properties of HSC. Local material "Kaolin Clay" was prepared as a pozzolana and the final product confirms the physical and chemical requirements of natural pozzolana. Eight mixes of the HSC with partial cement were replaced by HRM and SF (either individually or in combination). The effect of HRM and SF on the compressive, flexural strength, splitting tensile, impact resistance and modulus of elasticity of the HSC were studied. The results showed that the mix with 10% of HRM provided higher effect on the mechanical properties and impact resistance of the HSC. In addition, the HSC with the combined of 5% SF and 5% HRM exhibited greater performance and more economic than other mixes.

Keywords: HSC, HRM, SF, impact resistance and strength

1. Introduction:
High Strength Concrete (HSC) is defined as a concrete with high performance and strength. To date, there are no recognised standard design procedures for strength required of HSC. ACI Committee 363R [1] classified HSC as a concrete with a compressive strength greater than 40 MPa. HSC can be achieved by optimizing the characteristics of the cementing medium, aggregates, proportions of the paste, bond between paste and aggregate (the interfacial zone), mixing, consolidation and curing [2]. Several researchers investigated the properties of concrete with silica fume (SF) [3-6]. They improved the strength of concrete and SF with time. The result showed that the main contribution of SF on the strength development in hardening stage with normal curing temperature takes place with three days. Metakaolin (HRM) is a supplementary cementitious material (SCM) with high reactivity as class N pozzolana specifications according to ASTM C 618-05) [7]. Poon et al. [8] reported that kaolin clays are available in Ramadi west desert of Iraq with two types, which are white and red kaolin.

The white kaolin is available as pure and lenticular sediment with an average thickness of about 4.8 m in the Dewkhla region 60 km north of Rutba, west of Iraq. However, red kaolin contains impurity with different thickness lenticular sediment and a large proportion of "Fe2O3" compared to white kaolin which is available in A′amij valley (54 km east of Rutba). Kaolin has...
different colors due to its impurity according to $\text{Si}_2\text{O}_3$ layers (tetrahedral coordination) and $\text{AlO(OH)}_2$ (octahedral coordination) as shown in Figure 1. The main characteristics of mineral clay are electric neutral crystalline with fine particle and plate as the morphology which allows the particles to move easily over others that causes an increase in the physical properties such as softness, soapy feel and easy cleavage [9].

Figure 1. Atomic arrangements of (a) Silica layers and (b) Alumina layers of kaolin, where: • Si in (A) or Al in (B) ; ○ Oxygen; □ Hydroxyl [9].

Kaolin is quite stable under normal conditions but when it is heated from 650 to 900 °C, it lost 14% of its mass. This heating or calcination break down the kaolin’s structure and the $\text{AlO(OH)}_2$ and $\text{Si}_2\text{O}_3$ layers become puckered and miss their long – range order. The result of this dihydroxylation and disorder, metakaolin is produced with high reactive transition phase. Metakaolin is amorphous pozzolana with latent hydraulic properties which is used as a supplementary cementitious material [10]. Many researchers studied the effect of SF on the concrete properties. However, no researchers have focused on the effect of HRM (individually or combined) with SF on the properties of HSC, although the availability of raw materials in the country of the researcher (Iraq) which is cheaper than the SF. The aim of this study is to investigate the effect of HRM and/or SF on the properties of HSC.

2. Experimental programme:
2.1 Material preparation
2.1.1 Cement
Portland cement with strength greater than 15 MPa for 3 days and 23 MPa for 7 days with the fineness of 2300 cm$^2$/gm according to Iraqi specification No.5 / 1984 [10].

2.1.2 Aggregate
Natural sand (0-4.75mm) was used as fine aggregate and (5-14 mm) crushed gravel as coarse aggregate from Al-Najaf sea region according to Iraqi specification No.45/1984-2 [11].
2.1.3 Superplasticizer (SP) (High Range Water Reducing Agent)
Glenium® 54; (modified polycarboxylic ether), type A&F was used as a superplasticizer according to ASTM C494–05 [12].

2.1.4 Silica Fume
Silica Fume (SF) was used with extremely fine spherical particles that contains high amorphous silicon dioxide according to ASTM C1240–03 [13].

2.1.5 High reactivity metakaolin
High reactivity metakaolin is one of the supplementary cementing materials. It is produced by calcining purified kaolin clay to relegate the chemically bound water and destroy the crystalline structure as shown in equation (1).

\[
\text{(Kaolin)} \xrightarrow{(700 - 800) \text{C}^\circ} \text{(HRM)} \xrightarrow{\text{Steam}} \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O} + 2\text{H}_2\text{O} \quad \ldots (1)
\]

White kaolin clay was grounded by the air blast technique which was burned and converted to HRM. This process was prepared under different temperature which were 600, 700 and 800 C°. The results indicated that the 700 ± 10 C° was the optimum degree to produce the HRM. The amount of (Al\(_2\)O\(_3\) + SiO\(_2\) + Fe\(_2\)O\(_3\)) was greater than the requirements of ASTM C618–05 [6].

2.2 Materials and mix design
Ordinary Portland Cement (CEM I) with natural sand and crushed gravel were mixed together. Different percentage of SP, SF and HRM were used with w/c ratio of 0.44. Eight mixes of HSC were prepared according to Building Research Establishment Method as shown in Table 1.

2.3 Test specimens
100 mm cube was used for compression test according to BS 12390-3 [14]. ASTM C 496-04 [15] recommends a cylinder size of 150 mm diameter and 300 mm height; however, it allows alternative standard sizes. In this study, a smaller standard cylinder of 100 mm diameter × 200 mm height was used to measure the splitting tensile strength of the HSC. Flexural strength was measured by using beam with dimensions of 100 mm cross section and 400 mm length according to the ASTM C78-02 [16]. Compression, tensile and flexural strength were conducted at 7, 28, 56 and 91 days. However, cylinder size of 150 mm diameter and 300 mm height was used for determined modulus of elasticity (E\(_s\)) at 28 days according to ASTM C469-02 [17]. Impact test or drop weight test was used to measure impact resistance [20] as shown in Figure 2.
Table 1. Mix proportions for HSC (kg/m$^3$)

| Mix Proportion | Con. | SP | SP10SF | SP5HRM | SP10HRM | SP15HRM | SP5SF5HRM | SP5SF10HRM |
|----------------|------|----|--------|---------|---------|---------|-----------|------------|
| Cement         | 550  | 550| 495    | 522.5   | 495     | 467.5   | 495       | 467.5      |
| Mix constituents (kg/m$^3$) | | | | | | | | |
| Sand           | 640  | 640| 640    | 640     | 640     | 640     | 640       | 640        |
| Gravel         | 975  | 975| 975    | 975     | 975     | 975     | 975       | 975        |
| Water          | 214.5| 137.5| 137.5 | 137.5   | 137.5   | 137.5   | 137.5     | 137.5      |
| Water reduction (%) | – | 35.89 | 35.89 | 35.89 | 35.89 | 35.89 | 35.89 | 35.89 |
| w/c or w/cm to give slump 100 ± 10 mm | 0.39 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| HRM (kg/m$^3$) | – | – | – | 27.5 | 55 | 82.5 | 27.5 | 55 |
| SF (kg/m$^3$)  | – | – | 55 | – | – | – | 27.5 | 27.5 |
| SP Liter/ 100kg cement | – | 1.1 | 1.7 | 1.2 | 1.32 | 1.4 | 1.33 | 1.55 |

3. Results and discussion

3.1 Compressive strength

Compressive strength of the HSC according to BS EN 12390-3 [14] at 7, 28, 56 and 91 days are shown in Figure 4. The result showed that all the concrete mixes exhibit continuous increase in strength with the time. This phenomenon could refer to the continuity hydration of cement.
which took place when new hydration products were formed within the concrete mass. Concrete mix containing SP showed a significant increase in the strength at all age compared to that without any additions (control) which increased by 22.3%, 22.8%, 27.7% and 29.7% at 7, 28, 56 and 91 days respectively. This behaviour may due to a significant effect of water reduction as a result of the inclusion of this type of chemical admixture for a given workability as shown in Figure 3.

**Figure 3.** Compressive strength of the HSC with different curing regimes.

The compressive strength of the HSC with SP10HRM greater than with SP10SF by (7.4%, 8.3%, 8.9% and 9.2%) and with SP by (24.7%, 46.3%, 38.3% and 36.1%) at 7, 28, 56 and 91 days due to the high reactivity of metakaolin when it was partially replaced from cement as shown in Figure (1). There are many factors which effect on concrete reaction such as filler, acceleration of portland cement hydration and the pozzolanic reaction of HRM with Ca(OH)$_2$ [21]. In contrast, AL-Hadithi 2003 [22] discovered that there was slightly reduction in compressive strength at 7 and 28 days for HRM superplasticizer compared to corresponding superplasticizer concrete mix due to low specific surface area of high reactivity metakaolin.

### 3.2 Splitting tensile strength

Splitting tensile strength of the HSC according to ASTM C 496-04 [15] at 7, 28, 56 and 91 days are shown in Figure 4. The cracking behavior, stiffness and durability of the concrete affected by this test. The results indicated that there was a considerable increase in splitting tensile strength of the HSC with the SP at 7, 28, 56 and 91 days which increased by 15.15%, 14.06%, 8.81% and 5.37% respectively compared to the control. This phenomenon referred to the decrease in water content caused by a reduction in the porosity. The higher splitting tensile strength were obtained for HSC with SP5SF5HRM specimens which were greater that with SP10SF by 9.75%, 10.13%, 8.56% and 4.26%, with SP10HRM by 2.27%, 5.84%, 3.89% and 1.38% and with SP5SF10HRM by 5.63%, 8.66%, 7.64% and 3.83% respectively at 7, 28, 56 and 91 days. This behaviour could refer to the effect of SF and HRM on the porosity of the
cement paste up to 7 days. SF is finer than HRM which fills the voids between the granules of cement and HRM. However, HRM contributes continuous a decrease in the porosity of concrete. So SF and HRM provide lower porosity than the control at both early and later age.

Figure 4. Tensile strength of the HSC with different curing regimes.

3.3 Flexural strength

Flexural strength of the HSC according to ASTM C78-02 [16] at 7, 28, 56 and 91 days are shown in Figure 5. The results indicated that the flexural strength of HSC with SP10SF exhibit higher strength than that with SP, which increased by 12.4%, 8.4%, 7.8% and 9.9% at 7, 28, 56 and 91 days respectively. The HSC with 5SP,5SF and 5HRM had greater strength than with SP by 25.76%, 24.63%, 26% and 29.95%, with P10SF by 11.9%, 14.98%, 16.88% and 18.15%, with SP10HRM by 11.9%, 14.98%, 16.88% and 18.15% and with SP5SF10HRM by 6.53%, 9.63%, 10.48% and 12.77% at 7, 28, 56 and 91 days respectively as shown in Figure 6. The performance of the HSC with SP5SF5HRM over all mixes is attributed to the fact that with high activity of pozzolana (SF). Its reaction may start when calcium and hydroxyl ions are available from the hydration of Portland cement compounds. In pore size refinement a minor hydration product will be formed due to the pozzolanic reaction and formed CSH gel characterized by its low density and micro porous. When the gel fills the large capillary voids, pore structure will be developed. However, the grain size refinement means that the pozzolanic reaction effects of substitution of Ca(OH)$_2$ oriented crystals which knowns its large volume, small crystals with weak crystalline reaction products. So, the interfacial transition zone should be enhanced. Mehta and Monteiro, 2006 [23] explained that the reduction in micro cracking and strengthen the transition zone is due to the process of refinement of pore and grain size causes an increase in the strength of concrete.
Figure 5. Flexural strength of the HSC with different curing regimes.

3.4 Modulus of elasticity (E)

The modulus of elasticity (E) is mainly affected by the nature of the aggregates and cement paste. Additional effects are provided by the bond and arrangement between the particles [1]. The modulus of elasticity of HSC at 28 days range from 37-47 GPa as shown in Figure 7. The greatest value was with SP which was higher than the control by 13.5% because of the water reduction. In addition, the E value of HSC with SP10HRM is greatest than SP, SP10SF, SP5HRM and SP15HRM by 9.5%, 3.4%, 7.7% and 5.7% respectively due to the HRM which effects on cement hydration and forms microstructure as shown in Figure 6. In addition, HRM can physically disperse cement floc and expose great surface area of cement to normal hydration especially at age of 28 days resulting more dense and uniform hydrated structure with lower porosity. The increasing in the particulate packing of the concrete due to the HRM which can restrict the water free movement in the plastic concrete caused by tortuosity of the flow channels and consequently reduce bleeding [24]. This lead to improve the bond between aggregate particles and cement paste which causes denser interfacial zone. Furthermore, the pozzolanic reaction of the HRM increases the modulus of elasticity of concrete specimens at different ages which was lower than the compressive strength. This behaviour can refer to an increase in aggregate/binder ratio which agrees with Chemrouk and Hamrat 2002 2002 [25] discovered, when the modulus of elasticity of High-Performance Concrete (HPC) increased with an increase in the compressive strength.
3.5 Impact resistance

The impact resistance of the HSC mixes with the numbers of blow to cause the complete failure are shown in Figure 7. The results show that all the HSC mixes completely failed without obtaining the first visible crack. This indicates that the HSC is brittle material and the failure occurs suddenly. The impact resistance of the HSC with SP is greater than the control by 50%. The failure modes under impact load of the HSC specimens is shown in Figure 9. For mixes containing pozzolanic materials, the HSC with SP10HRM mix showed highest impact resistance compared to that with SP, SP10SF, SP5HRM and SP15HRM which increased by 166.7%, 52.4%, 64.1% and 42.3% respectively as shown in Figure (8). However, the HSC with SP5SF5HRM specimens showed greatest increase in impact resistance compared to that with SP, SP10SF, SP10HRM and SP5SF10HRM by 235%, 91.4%, 25.6% and 54.6% respectively. This due to the combined effect of HRM and SF.
4. Conclusions

1. HRM is considered a mineral admixture. It is used to produce the HSC because of its texture which requires lower dosage than SF.
2. The use of SP causes a significant decrease in the quantity of water which is required to produce the HSC with optimum properties than the control.
3. The use of binary mixes has greater performance than singly mixes and reduce the cost of using the SF by using lower replacement level and reduce the superplasticizer dosage.
4. The HSC with SP5SF5HRM mix had greatest compressive, tensile, flexural strength, modulus of elasticity and impact resistance than all the mixes.
5. The water content has higher effect on the impact resistance of HSC than compressive strength.

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