Research Article

Development of UHPC Mixtures Utilizing Natural and Industrial Waste Materials as Partial Replacements of Silica Fume and Sand

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In the exploratory study presented in this paper, an attempt was made to develop different mixtures of ultrahigh performance concrete (UHPC) using various locally available natural and industrial waste materials as partial replacements of silica fume and sand. Materials such as natural pozzolana (NP), fly ash (FA), limestone powder (LSP), cement kiln dust (CKD), and pulverized steel slag (PSS), all of which are abundantly available in Saudi Arabia at little or no cost, were employed in the development of the UHPC mixtures. A base mixture of UHPC without replacement of silica fume or sand was selected and a total of 24 trial mixtures of UHPC were prepared using different percentages of NP, FA, LSP, CKD, and PSS, partially replacing the silica fume and sand. Flow and 28-d compressive strength of each UHPC mixture were determined to finally select those mixtures, which satisfied the minimum flow and strength criteria of UHPC. The test results showed that the utilization of NP, FA, LSP, CKD, and PSS in production of UHPC is possible with acceptable flow and strength. A total of 10 UHPC mixtures were identified with flow and strength equal to or more than the minimum required.

1. Introduction

UHPC, also known as reactive powder concrete (RPC), exhibits excellent mechanical and durability properties and is one of the latest advances in concrete technology. The high compressive strength (more than 150 MPa), tensile strength, toughness, and ductility along with negligible water and chloride permeability, and therefore high durability, of this new concrete material make it UHPC [1]. The basic principle on which UHPC is based is to achieve a cement matrix as dense as possible (by reducing microcracks and capillary pores in the cement matrix) and a dense transition zone between cement matrix and aggregate. These requirements of UHPC are achieved by enhancing the homogeneity by replacing coarse aggregate by fine quartz sand with a maximum size of 600 μm [2]; improving the properties of cement matrix by the addition of pozzolanic admixture, such as silica fume in the range of 15% to 30% of the mass of cement [2, 3]; reducing water to binder ratio to below 0.2 (by mass) with the help of a high dosage of superplasticizer; optimizing the particles grading to achieve maximum packing density of mixture; adding an adequate amount of steel fibers to achieve ductility; and adopting a suitable method of curing [4–7].

As a result of extensive research carried out globally during the last few years, the production of UHPC is no longer limited within the domain of patented concrete materials. However, use of a very high amount of silica fume and the requirement of fine quartz sand in UHPC put bottlenecks in producing UHPC in places where such ingredients are locally unavailable. In order to mitigate this problem, the possibility of using locally available alternative materials as partial replacement for silica fume and fine quartz sand should be explored. Several studies are reported on production of UHPC utilizing different mineral admixtures [8–11].

Through a study on use of pulverized fly ash, pulverized granulated blast furnace slag, and silica fume as
a partial replacement of cement, Yazıcı [8] has found that high strength concrete with compressive strength more than 170 MPa can be produced. Basalt and quartz powder were used as an aggregate in the mixtures and three different curing methods (standard, autoclave, and steam curing) were applied to the specimens.

Yazıcı et al. [9] have reported the effect of partial replacement of the cement and silica fume (SF) by fly ash (FA) and/or ground granulated blast furnace slag (GGBFS) on the performance of RPC. Their test results indicated that the utilization of FA and/or GGBFS in RPC is possible without significant loss of mechanical performance. They concluded that the RPC containing high volume binary (SF-FA or SF-GGBFS) or ternary (SF-FA-GGBFS) blends have satisfactory mechanical performance. In other words, utilization of FA and/or GGBFS in RPC production is very effective.

In another study, Yazıcı et al. [10] have investigated the mechanical properties (compressive strength, flexural strength, and toughness) of RPC produced with class-C FA and GGBFS under different curing conditions (standard, autoclave, and steam curing). They have observed that by increasing the GGBFS and/or FA content, the toughness of RPC increases under all curing regimes considerably. Furthermore, SEM micrographs revealed dense microstructure of RPC. The test results also showed that RPC containing high volume mineral admixtures has satisfactory mechanical performance. Although the cement and silica fume contents of these mixtures were lower than the conventional RPC, compressive strength exceeded 200 MPa after standard water curing. Finally, they reported that the GGBFS and/or FA can also be used as a fine silica source for RPC.

Van Tuan et al. [11] investigated the possibility of using rice husk ash (RHA) to produce UHPC. RHA is an agricultural waste which possesses a very high amount of amorphous SiO₂ and a large surface area and is therefore classified as a “highly active pozzolana.” The result showed that the compressive strength of UHPC incorporating RHA, can be achieved in excess of 150 MPa with normal curing regime. The interesting point is that the effect of RHA on the development of compressive strength of UHPC is larger than that of SF. Besides, the sample incorporating the ternary blend of cement with 10% RHA and 10% SF showed better compressive strength than that of the control sample without RHA or SF. This blend proved to be the optimum combination for achieving maximum synergic effect.

Taking notes of the research work pertaining to the utilization of various natural and waste materials in producing UHPC, an attempt was made under the present work to develop alternative mixtures of UHPC using NP, FA, LSP, CKD, and PSS, the materials locally available in Saudi Arabia. The main objective of this study was to explore the possibility of replacing microsilica and dune sand contents of a typical base mixture of UHPC possessing a flow of 230 mm and 28-d compressive strength of 161 MPa. Using permutations and combinations of the replacements of microsilica and dune sand, a set of 24 UHPC trial mixtures were designed using absolute volume method. These mixtures were prepared and tested for flow before casting to obtain specimens for compressive strength testing after 28 days of water curing.

### Table 1: Chemical composition of cement.

| Constituent         | Weight % |
|---------------------|----------|
| CaO                 | 64.35    |
| SiO₂                | 22.0     |
| Al₂O₃               | 5.64     |
| Fe₂O₃               | 3.80     |
| K₂O                 | 0.36     |
| MgO                 | 2.11     |
| Na₂O                | 0.19     |
| Equivalent alkalis  | 0.33     |
| SO₃                 | 2.10     |
| Loss on ignition    | 0.7      |

### Table 2: Grading of the dune sand used as aggregate.

| ASTM sieve number | Size (mm) | Percentage passing (%) |
|-------------------|-----------|------------------------|
| 4                 | 4.75      | 100                    |
| 8                 | 2.36      | 100                    |
| 16                | 1.18      | 100                    |
| 30                | 0.6       | 75                     |
| 50                | 0.3       | 10                     |
| 100               | 0.15      | 5                      |

### 2.1. Materials

#### 2.1.1. Cement
Ordinary Portland cement conforming to ASTM C150 type I with a specific gravity of 3.15 was used in all the UHPC mixtures. Sufficient amount of cement was procured and stockpiled safely to prevent hardening of cement. The chemical composition of cement is shown in Table 1.

#### 2.1.2. Aggregate
Dune sand, abundantly available in the deserts of Saudi Arabia, was used in this study as aggregate in its naturally graded form. Table 2 shows the grading of the dune sand used. The specific gravity of fine aggregate was 2.53, and the water absorption was 0.4%.

#### 2.1.3. Superplasticizer
The superplasticizer used in all the trial mixtures was Glenium 51. It is a new generation polycarboxylic-based ether hyperplasticiser. It was sourced from a local supplier in Saudi Arabia. Its technical data, as obtained from the manufacturer, is shown in Table 3.

#### 2.1.4. Microsilica (MS)
Elkem microsilica, generated from the carbothermic reduction of quartz and quartzite in electric...
Table 3: Technical data of Glenium 51 used as superplasticizer.

| Item                     | Description          |
|--------------------------|----------------------|
| Appearance               | Brown liquid         |
| Specific gravity at 20°C | 1.08 ± 0.02 g/cm³    |
| pH-value at 20°C         | 7.0 ± 1.0            |
| Alkali content           | ≤5.0                 |
| Chloride content         | ≤0.1%                |

Table 4: Chemical composition of the microsilica.

| Constituent | Weight % |
|-------------|----------|
| SiO₂        | 92.5     |
| Al₂O₃       | 0.72     |
| Fe₂O₃       | 0.96     |
| CaO         | 0.48     |
| MgO         | 1.78     |
| K₂O         | 0.84     |
| Na₂O        | 0.5      |
| Loss on ignition | 1.55 |

arc furnaces in the production of silicon and ferrosilicon alloys, containing 85–95% SiO₂ with very fine vitreous particles (fines in the order of 10 times finer than that of cement), was used in this study. The chemical composition of the microsilica used in this study is shown in Table 4. The microsilica had a specific gravity of 2.25.

2.2. Natural and Industrial Waste Materials. Several natural and industrial waste materials are abundantly available in Saudi Arabia at relatively lower costs, which can be used as replacing materials in producing UHPC concrete mixtures. Details of five such materials are presented in Table 5. These materials were used in varying percentages as partial replacements of microsilica and sand. It can be observed from Table 5 that while NP and FA are rich in silica, LSP, CKD, and PSS are rich in lime. Considering this fact, maximum replacement of microsilica by NP and FA was kept up to 80% whereas the replacement of microsilica by LSP, CKD, and PSS was limited to a maximum level of 20%.

2.3. Base Mixture of UHPC. A typical mixture of UHPC developed earlier by the authors with a flow of 230 mm and 28-d compressive strength of 161 MPa was considered as a base mixture without replacement of microsilica and sand by the natural and industrial waste materials. The quantities of constituent materials for producing 1 m³ of the selected base UHPC mixture are shown in Table 6. As can be observed from Table 6, base mixture contains the following: cement forming about 36.2% weight of the mixture, fine dune sand forming about 40.5% by weight of the mixture, Elkem microsilica forming about 8.9% by weight of the mixture, a water-to-binder ratio of about 0.145 (by weight), the superplasticizer (Glenium 51) forming about 1.6% by weight of the mixture (3.5% by mass of binder), water forming about 6.5% by weight of mixture, and steel fibers (with diameter of about 0.15 mm, length of about 12.7 mm, and tensile strength over 2500 MPa) forming about 6.3% by weight of the mixture.

2.4. Trial Mixtures of UHPC Using Natural and Industrial Waste Materials. For preparing trial mixtures of UHPC, microsilica (out of 220 kg/m³ used in base mixture) was partially replaced by NP and FA in the range of 40%, 60%, and 80% and by LSP, CKD, and PSS in the range of 5%, 10%, and 20%. Dune sand (out of 1005 kg/m³ used in base mixture) was partially replaced by LSP, CKD, and PSS in the range of 5%, 10%, and 20%. This way a total of 24 trial mixtures of UHPC were considered. The design of all these trial mixtures was carried out using absolute volume method. The water/binder ratio and quantities of water, cement, superplasticizer, and steel fiber were kept constant at values the same as those for the base mixture of UHPC. The estimated quantities of all ingredients for producing 1 m³ of the trial mixtures are presented in Table 7 along with the ID of each of the UHPC mixtures.

2.5. Preparation and Testing of Trial Mixtures of UHPC. For preparing the UHPC trial mixtures, batching of all ingredients was done as per their quantities listed in Table 7 and a step-by-step procedure for charging and mixing was adopted, as outlined below.

(i) Cement, silica fume, and dune sand were charged together in a Hobart planetary high speed mixer and allowed to get mixed slowly for a duration of 2 minutes.

(ii) Half of the total quantity of superplasticizer was mixed with water and the mixture of water and superplasticizer was added slowly to the dry mixture of cement, silica fume, and dune sand. The mixing was continued for 8 to 10 minutes until the dry mixture is converted into granules.

(iii) After formation of the granules, the remaining half of the superplasticizer was added slowly and mixing was continued for about another 5 minutes until the mixture was turned into a homogenous fluid.

(iv) Finally, the steel fibers were added to the mixture slowly in small amounts over the course of the next 2 minutes. After the fibers were charged completely, the mixing was continued for a further period of 3 minutes to ensure that the fibers were well dispersed in the prepared mixture of UHPC.

(v) The prepared mixture of UHPC was then taken for first conducting flow test and then casting the specimens for compressive strength. It should be noted that the mixing times in each step are relative and are only specifically applicable to the mixer used in this study.

ASTM C1437 standard test method for measuring flow of hydraulic cement mortar was used to determine flow of the trial mixtures of UHPC. For measuring flow, a minislump cone was filled with the UHPC mixture and then removed slowly to allow the mixture to flow evenly on the table and
Table 5: Details of the materials used as partial replacements of microsilica and sand.

| Replacing materials       | Source                                           | Specific gravity | CaO (% by mass) | SiO₂ (% by mass) |
|--------------------------|--------------------------------------------------|------------------|-----------------|------------------|
| Natural pozzolana (NP)   | Volcanic rocks in Western Province of Saudi Arabia | 3.00             | 8.06            | 42.13            |
| Fly ash (FA)             | Local ready mixed concrete company in Saudi Arabia | 2.25             | 8.38            | 45.30            |
| Lime stone powder (LSP)  | Local aggregate quarry in Abu Hadriyah, Saudi Arabia | 2.60             | 45.70           | 11.79            |
| Cement kiln dust (CKD)   | Saudi Cement Company, Jeddah, Saudi Arabia       | 2.79             | 49.30           | 17.10            |
| Pulverized steel slag (PSS) | Local steel manufacturing company in Saudi Arabia | 3.75             | 40.80           | 16.47            |

Table 6: Quantities of constituents for producing 1 m³ of the base UHPC mixture.

| Cement kg | Fine dune sand kg | Water kg | Microsilica (MS) kg | Steel fibers kg | Plasticizer Glenium 51 kg |
|-----------|-------------------|----------|--------------------|----------------|--------------------------|
| 900       | 1005              | 163      | 220                | 157            | 40                       |

then the flow table was lifted up and dropped down for 20 times to allow the mixture to spread on the flow table. The average diameter of the spread mixture was recorded as flow value for the mixture. The acceptable value of mixture flow ranges between 180 mm and 220 mm. The flow test was completed and mixture was cast within first 20 minutes of the mixing to obtain specimens for compressive strength test. The casting of the specimens for compressive strength test was done by pouring the mixture into moulds kept on a vibrating table and then vibrating the table for about 30 seconds after filling to consolidate the mixture. After casting, the specimens were covered with plastic sheet for 24 hours in the laboratory environment (22 ± 3°C) and then submerged in water tank for 28-d curing before testing for compressive strength.

3. Results and Discussion

The flow and 28-d compressive strength test results for all trial mixtures and base mixture are presented in Table 8. As can be observed from Table 8, the flow and 28-d compressive strength of trial UHPC mixtures varied in a wider range of 150 to 255 mm and 125 to 163 MPa, respectively. As can be seen from Table 7, the sand content of the trial mixtures varies in a wider range of 764 to 1055 kg/m³ due to replacement of microsilica and dune sand by the replacing materials. To observe the effect of variation of sand content on flow and compressive strength, Figures 1 and 2 were plotted using the data from Table 8. It can be observed from Figure 1 that the flow of the mixtures is slightly improved with increase in the sand content. Figure 2 indicates that there is no clear trend of variation of compressive strength with change in the sand content.

For examining the acceptable levels of partial replacements of microsilica and dune sand by the replacing materials, the flow and 28-d compressive strength test results were plotted as shown in Figures 3, 4, 5, 6, 7, and 8. The minimum acceptable values of flow and 28-d compressive strength were considered as 180 mm and 150 MPa, respectively.

The plots of flow values obtained for UHPC mixtures with NP and FA replacing microsilica, as shown in Figure 3, indicate that the flow is more than minimum limit at all levels...
Table 7: Quantities of all ingredients for producing 1 m³ of the trial UHPC mixtures.

| Partial replacement of microsilica and sand | Mixture ID | Cement kg | Sand kg | Water kg | Microsilica (MS) kg | Replacing material kg | Steel fibers kg | Plasticizer Glenium (51 kg) |
|--------------------------------------------|------------|-----------|---------|----------|---------------------|----------------------|-----------------|-----------------------------|
| Base mixture without replacement           | BMWR       | 900       | 1005    | 162      | 220                 | 0                    | 157             | 40                          |
| Natural pozzolana (NP) replacing 40%, 60%, and 80% microsilica (MS) | NP40RMS    | 900       | 1030    | 162      | 132                 | 88                   | 157             | 40                          |
|                                            | NP60RMS    | 900       | 1042    | 162      | 88                  | 132                  | 157             | 40                          |
|                                            | NP80RMS    | 900       | 1055    | 162      | 44                  | 176                  | 157             | 40                          |
| Fly ash (FA) replacing 40%, 60%, and 80% microsilica (MS) | FA40RMS    | 900       | 1005    | 162      | 132                 | 88                   | 157             | 40                          |
|                                            | FA60RMS    | 900       | 1005    | 162      | 88                  | 132                  | 157             | 40                          |
|                                            | FA80RMS    | 900       | 1005    | 162      | 44                  | 176                  | 157             | 40                          |
| Lime stone powder (LSP) replacing 5%, 10%, and 20% microsilica (MS) | LSP05RMS   | 900       | 1000    | 162      | 209                 | 11                   | 157             | 40                          |
|                                            | LSP10RMS   | 900       | 995     | 162      | 198                 | 22                   | 157             | 40                          |
|                                            | LSP20RMS   | 900       | 985     | 162      | 176                 | 44                   | 157             | 40                          |
| Cement kiln dust (CKD) replacing 5%, 10%, and 20% microsilica (MS) | CKD05RMS   | 900       | 1008    | 162      | 209                 | 11                   | 157             | 40                          |
|                                            | CKD10RMS   | 900       | 1010    | 162      | 198                 | 22                   | 157             | 40                          |
|                                            | CKD20RMS   | 900       | 1015    | 162      | 176                 | 44                   | 157             | 40                          |
| Pulverized steel slag (PSS) replacing 5%, 10%, and 20% microsilica (MS) | PSS05RMS   | 900       | 1010    | 162      | 209                 | 11                   | 157             | 40                          |
|                                            | PSS10RMS   | 900       | 1015    | 162      | 198                 | 22                   | 157             | 40                          |
|                                            | PSS20RMS   | 900       | 1025    | 162      | 176                 | 44                   | 157             | 40                          |
| Lime stone powder (LSP) replacing 5%, 10%, and 20% sand | LSP05RSAND | 900       | 931     | 162      | 220                 | 47                   | 157             | 40                          |
|                                            | LSP10RSAND | 900       | 868     | 162      | 220                 | 87                   | 157             | 40                          |
|                                            | LSP20RSAND | 900       | 764     | 162      | 220                 | 153                  | 157             | 40                          |
| Cement kiln dust (CKD) replacing 5%, 10%, and 20% sand | CKD05RSAND | 900       | 962     | 162      | 220                 | 48                   | 157             | 40                          |
|                                            | CKD10RSAND | 900       | 922     | 162      | 220                 | 92                   | 157             | 40                          |
|                                            | CKD20RSAND | 900       | 851     | 162      | 220                 | 170                  | 157             | 40                          |
| Pulverized steel slag (PSS) replacing 5%, 10%, and 20% sand | PSS05RSAND | 900       | 972     | 162      | 220                 | 49                   | 157             | 40                          |
|                                            | PSS10RSAND | 900       | 942     | 162      | 220                 | 94                   | 157             | 40                          |
|                                            | PSS20RSAND | 900       | 886     | 162      | 220                 | 177                  | 157             | 40                          |

Table 8: Flow and compressive strength test results.

| Mixture ID | Flow (mm) | 28-d compressive strength (MPa) | Mixture ID | Flow (mm) | 28-d compressive strength (MPa) |
|------------|-----------|---------------------------------|------------|-----------|---------------------------------|
| BMWR       | 230       | 161                             | LSP05RSAND | 220       | 125                             |
| NP40RMS    | 225       | 147                             | LSP10RSAND | 215       | 163                             |
| NP60RMS    | 195       | 154                             | LSP20RSAND | 185       | 132                             |
| NP80RMS    | 200       | 136                             | CKD05RSAND | 180       | 153                             |
| FA40RMS    | 230       | 150                             | CKD10RSAND | 200       | 135                             |
| FA60RMS    | 210       | 158                             | CKD20RSAND | 150       | 100                             |
| FA80RMS    | 210       | 143                             | PSS05RSAND | 210       | 161                             |
| LSP05RMS   | 215       | 159                             | PSS10RSAND | 185       | 153                             |
| LSP10RMS   | 220       | 146                             | PSS20RSAND | 180       | 160                             |
| LSP20RMS   | 255       | 152                             |            |           |                                 |
| CKD05RMS   | 180       | 144                             |            |           |                                 |
| CKD10RMS   | 230       | 142                             |            |           |                                 |
| CKD20RMS   | 220       | 152                             |            |           |                                 |
| PSS05RMS   | 200       | 134                             |            |           |                                 |
| PSS10RMS   | 215       | 140                             |            |           |                                 |
| PSS20RMS   | 225       | 161                             |            |           |                                 |
of replacement. However, as can be seen from Figure 4, it is found that the minimum required 28-day strength can be achieved at an optimum replacement level of 60% for both NP and FA. Therefore, it can be concluded that the optimum dosages of NP and FA for partially replacing the microsilica are typically found to be 60%. Like the case of mixtures with NP and FA, plots shown in Figure 5 indicate that the UHPC mixtures with LSP, CKD, and PSS, partially replacing the microsilica, can achieve minimum required flow at all levels of replacements. However, the minimum required 28-d compressive strength of 150 MPa can be obtained only at a replacement level of 20% for each of the three replacing materials (LSP, CKD, and PSS). Thus, the optimum level of partial replacement of microsilica by LSP, CKD, and PSS is typically 20%.

Referring to Figures 7 and 8 for examining the optimum levels of partial replacement of dune sand by LSP, CKD, and PSS, it is observed that all three levels of partial replacements of dune sand by PSS are acceptable because minimum required flow and strength are satisfied with all three replacement levels for PSS. All three levels of replacement by LSP also satisfy the minimum required flow but the minimum 28-d compressive strength is achievable only at 10% of replacement.
Figure 8: Variation of compressive strength with replacement of sand by LSP, CKD, and PSS.

Table 9: Selected UPHC mixtures meeting the criteria for minimum required flow (180 mm) and 28-d compressive strength (150 MPa).

| Mix ID   | Flow (mm) | 28-d compressive strength (MPa) | 28-d flexural tensile strength (MPa) |
|----------|-----------|----------------------------------|-------------------------------------|
| BMWR     | 230       | 161                              | 31                                  |
| NP60RMS  | 195       | 154                              | 29                                  |
| FA60RMS  | 210       | 158                              | 32                                  |
| LSP20RMS | 255       | 152                              | 31                                  |
| CKD20RMS | 220       | 152                              | 25                                  |
| PSS20RMS | 225       | 161                              | 25                                  |
| LSP10RSAND | 215   | 163                              | 29                                  |
| CKD05RSAND | 180   | 153                              | 26                                  |
| PSS05RSAND | 210   | 161                              | 24                                  |
| PSS10RSAND | 185   | 153                              | 23                                  |
| PSS20RSAND | 180   | 160                              | 24                                  |

4. Conclusions

Based on the findings of the present study, the following conclusions can be drawn.

(i) The possibility of utilizing the natural and industrial waste materials considered in this study for development of UHPC mixtures as a partial replacement of microsilica as well as sand is confirmed. The outcomes of this study would be beneficial particularly in reducing the consumption of microsilica, which is relatively a costly material in producing UHPC in Saudi Arabia.

(ii) The optimum level of replacing microsilica by NP and FA was typically found to be 60%, whereas it was 20% in case of LSP, CKD, and PSS.

(iii) While the optimum levels of replacing dune sand by CKD and LSP were 5% and 10%, respectively, the PSS can be used to replace the dune sand at all three levels, 5%, 10%, and 20%, without compromising with the minimum required flow and 28-d compressive strength.

(iv) As listed in Table 8, a total of 10 mixtures of UHPC were developed utilizing natural and industrial waste materials as partial replacements of silica fume and dune sand. Apart from high compressive strength, these mixtures have about two to three times more flexural tensile strength as compared to traditional concrete with similar strength grade.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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