Effect of Silica Fume on two-stage Concrete Strength

H S Abdelgader$^{1,2}$ and A S El-Baden$^1$
$^1$Tripoli University, Faculty of Engineering, Civil Engineering Dept., Tripoli, Libya
E-mail: hakimsa@poczta.onet.pl

Abstract. Two-stage concrete (TSC) is an innovative concrete that does not require vibration for placing and compaction. TSC is a simple concept; it is made using the same basic constituents as traditional concrete: cement, coarse aggregate, sand and water as well as mineral and chemical admixtures. As its name suggests, it is produced through a two-stage process. Firstly washed coarse aggregate is placed into the formwork in-situ. Later a specifically designed self compacting grout is introduced into the form from the lowest point under gravity pressure to fill the voids, cementing the aggregate into a monolith. The hardened concrete is dense, homogeneous and has in general improved engineering properties and durability. This paper presents the results from a research work attempt to study the effect of silica fume (SF) and superplasticizers admixtures (SP) on compressive and tensile strength of TSC using various combinations of water to cement ratio (w/c) and cement to sand ratio (c/s). Thirty six concrete mixes with different grout constituents were tested. From each mix twenty four standard cylinder samples of size (150mmx300mm) of concrete containing crushed aggregate were produced. The tested samples were made from combinations of w/c equal to: 0.45, 0.55 and 0.85, and three c/s of values: 0.5, 1 and 1.5. Silica fume was added at a dosage of 6% of weight of cement, while superplasticizer was added at a dosage of 2% of cement weight. Results indicated that both tensile and compressive strength of TSC can be statistically derived as a function of w/c and c/s with good correlation coefficients. The basic principle of traditional concrete, which says that an increase in water/cement ratio will lead to a reduction in compressive strength, was shown to hold true for TSC specimens tested. Using a combination of both silica fume and superplasticisers caused a significant increase in strength relative to control mixes.

1. Introduction
Placement of concrete in the places that are difficult to reach, such as concrete repairing or underwater applications, is one of the challenging tasks for construction engineering, due to the risk of segregation and bleeding or washout of concrete constituents. Thus, the quality of concrete is highly influenced by its placement technique [1-3]. The goal when applying any of the placement techniques is to place

$^2$To whom any correspondence should be addressed.
concrete into the formwork with minimum segregation, minimum honeycombing and maximum possible homogeneity of the concrete constituents, in order to achieve a concrete with high performance and durability properties. Concrete time dependent deformations and consequently cracking have been a growing concern. This has been the case in modern concrete work due to the use of higher content of mineral and chemical admixtures, low water-to-cement ratio and extended exposure to severe conditions during service; all of which may contribute to increasing volume instability in concrete. For example, minimizing of shrinkage can be ensured by the usage of adequate mix proportions, thorough curing and the use of shrinkage compensating cement [4, 5]. It was attested that using non-traditional concrete in engineering applications has been considered as an efficient solution to overcome challenges of limitations of the use of normal conventional concrete. Such new types of concrete, which have been developed and produced, are completely different from the conventional concrete in the methods of mixing, handling, pouring, consolidation, behaviors, cost, etc. Based on the technology of ready-mix self-compacting concrete (SCC), a new type of non-conventional concrete has been introduced and named as: two-stage concrete (TSC) or slurry infiltrated concrete (SICON) [3]. As the name would suggest, TSC is produced through a two-stage process. Firstly washed coarse aggregate is placed in the designated destination. Later a specifically designed grout is introduced into the form from the lowest point under gravity pressure to fill the voids, cementing the aggregate into a monolith [3], as presented in figure 1. As concrete technology develops, basic grouts for TSC can be modified to produce structural concrete more effectively. Such grouts may be modified chemically by using suitable combinations of mineral admixtures, such as silica fume (SF) and superplasticizers, or mechanically by using a specially designed high-speed mixer. Silica fume imparts very good improvement to rheological, mechanical and chemical properties. It improves the durability of the concrete by reinforcing the microstructure through filler effect and thus reduces segregation and bleeding [6, 7].

![Figure 1. Two stage concrete basic technique.](image)

This paper presents the results from a research work attempt to study the effect of silica fume (SF) and superplasticizers admixtures (SP) on compressive and tensile strength of TSC using various combinations of water to cement ratio (w/c) and sand to cement ratio (c/s). Thirty six concrete mixes with different grout constituents were tested. From each mix twenty four standard cylinder samples of size (150mmx300mm) of concrete containing crushed aggregate were produced. The tested samples were made from combinations of w/c equal to: 0.45, 0.55 and 0.85, and three c/s of values: 0.5, 1 and 1.5. Silica fume was added at a dosage of 6% of weight of cement, while superplasticizer was added at a dosage of 2% of cement weight.
2. Experimental program and discussion

2.1. Selection of materials
Materials, mix proportions and sample preparation procedures will be presented in this section as follows.

**Cement.** Throughout the research, ordinary Portland cement (Type I) conforming to ASTM-C150 [8] was used. Different quality control laboratory tests were conducted and the results are tabulated in table 1.

**Water.** Ordinary potable water available in the laboratory was used.

**Fine Aggregate.** The fine aggregate used in the manufacture of grout was natural beach sand with specific gravity 2.68 and maximum size 2 mm, conforming to ASTM-C33 [9]. The grading of the fine aggregate obtained from the sieve analysis is shown in figure 2.

**Coarse Aggregate.** The coarse aggregate used was crushed dolomite limestone of specific gravity 2.68, crushing value of 18.83%, abrasion value of 23.81%, and absorption value of 1.66%. Two aggregates of maximum size 19 mm and 10 mm were combined together to obtain the best combined aggregate grading as shown in figure 2.

| Table1. Properties of cement. |
|-----------------------------|
| Test Name                  | Result | Specifications |
| Standard Consistency       | 28%    | 32-27%         |
| Initial setting Time       | 2:25 hr| ≥ 45 Min.      |
| Final Setting Time         | 3:40 hr| ≤ 10 hrs       |
| Soundness                  | 1 mm   | ≤ 10 mm        |
| Compressive strength (3 days) | 22 MPa | ≥ 21 MPa       |
| Compressive strength (7 days) | 30 MPa | ≥ 24 MPa       |
| Compressive strength (28 days) | 40 MPa | ≥ 39 MPa       |

![Figure 2. Fine aggregate and coarse aggregate sieve analysis grading.](image-url)
Chemical Admixture. A visocrete based superplasticizer (SP) imported from SIKA-company is the only kind of admixture used in this research. It is a liquid material with a chemical composition consisting mainly of naphthalene-formaldehyde derivative, trade name ‘SikaMent-163’. Superplasticizer was added at dosage rate of 2% by weight of cement. The superplasticizer dosage was mixed with the designated water and added after dry mixing of the mix constituents was completed.

Mineral Admixture. Silica fume (SF) powder containing 97% SiO$_2$ and having a specific surface area of about 20,000 m$^2$/kg was the only mineral admixture used in this research. The silica fume was used on dry basis as an additive at a rate of 6% by weight of cement.

2.2. Grout mix preparation

The selection of water-cement-sand ratios is more critical in TSC because the amounts of sand and water control the pumpability and propagation of grout, therefore, an essential requirement should be met in the production of TSC [5]. American Concrete Institute (ACI) method was used during this research to obtain the self-compacted grout mixtures proportions, followed by adjustments to the mix constituents to characterize the mixes for filling ability, passing ability and resistance to segregation [5]. The void content of the preplaced aggregate was 47 % and the bulk density – 1430 kg/m$^3$, based on a previous preliminary investigations conducted by the authors and others [5,7]. A total of thirty six mixes divided into four groups of concrete mixes were designed and implemented. Each group comprised a combination of nine mixes having the following constant definitions: 1 -The w/c ratio of: 0.45, 0.55 and 0.85. 2- c/s ratio of: 0.5, 1, 1.5. The first group was designed and implemented without using any chemical or mineral additives and was denoted in the text as (No Admixture). Superplasticizers were only used in the second group as a chemical additive at a dosage rate of 2% by weight of cement, denoted in the text as (SP). Silica fume was only used in the third group as a mineral additive at a dosage rate of 6% by weight of cement, denoted in this paper as (SF). A combination of both silica fume and superplasticizer was used in the fourth group with the same dosages as in the other groups and denoted in the text as (SP+SF). Grout preparation was accomplished by combining ingredients with an electric mixer for about two minutes in a dry basis then followed by other three minutes of wet mixing to achieve the desired grout uniformity and consistency after adding water and the other specified additives. Table 2 presents the contents of all the TSC mixes investigated.

| Mix No. | w/c  | c/s  | Cement (kg/m$^3$) | Sand (kg/m$^3$) | Water (kg/m$^3$) |
|---------|------|------|-------------------|----------------|-----------------|
| 1       | 1/0.5| 1/0.5| 524.093           | 262.046        | 235.841         |
| 2       | 0.45 | 1/1  | 438.367           | 438.367        | 197.841         |
| 3       | 1/1.5| 1/1  | 376.740           | 565.115        | 169.533         |
| 4       | 1/0.5| 1/0.5| 474.370           | 237.185        | 260.903         |
| 5       | 0.55 | 1/1  | 403.032           | 403.032        | 221.667         |
| 6       | 1/1.5| 1/1  | 350.345           | 525.518        | 192.689         |
| 7       | 1/0.5| 1/0.5| 369.268           | 184.634        | 313.877         |
| 8       | 0.85 | 1/1  | 324.550           | 324.550        | 275.867         |
| 9       | 1/1.5| 1/1  | 289.492           | 434.238        | 246.068         |
2.3. Methods of placement and testing
The placement of TSC was experimentally modelled as shown in figure 1. One injecting polyvinyl chloride (PVC) pipe 700 mm high and 20 mm in diameter was vertically inserted till about 20 mm from the bottom of the mould (150mmx300mm). The aggregate was cast slowly and gradually, being distributed as uniformly as possible inside the mould. The aggregate completely filled the entire mould and then the prepared grout mix was pumped directly through the injecting tube by gravity. After one day of casting all specimens were removed from their moulds and stored in water curing tanks in the laboratory climate. The experimental program consisted of a series of unconfined compression tests and split tensile tests on the samples prepared from different grout mixtures after 7, 28, 90 and 120 days of water curing in the laboratory climate. Cylindrical specimens of size 150 x 300 mm were prepared in the same manner and tested. On the other hand, grout specimens were tested in compression using standard cubes of size 100x100x100 mm. Nine specimens from each mix were prepared and tested in unconfined compression and split tension at 7, 28, 90 and 120 days, at a rate of three samples for each kind of tests. Unconfined compression tests on TSC cylinders were tested in accordance with standards (ASTM-C873) [10] using a universal hydraulic testing machine with a capacity of 2200 kilo newton (KN) and a rate of loading of approximately 7 KN per minute. The samples were subjected to loading till failure. Splitting tensile tests were also conducted on three specimens of each concrete according to the procedures outlined in (ASTM-C496) [11].

3. Analysis and discussion
3.1. Compressive strength test results
Table 3 reports compressive strength results at different ages for the tested TSC mixtures using various ratios of w/c, c/s and different chemical and mineral admixtures. Results indicted generally that the TSC mixtures exhibited comparable compressive strength trend with respect to the type of admixtures. Generally, at the same age and w/c ratio, it was observed that increasing c/s would reduce slightly the strength of TSC, which is obviously related to the reduction in flowability and passability of the grout, which leads to production of TSC microstructure with honeycombed structure with partial binding of the aggregate skeleton. Usage of SP enhances the flowability and the passability of the grout and leads to improved strength results. Moreover, using SF alone or in combination with SP exhibited better compressive strength results compared to the mixes with no admixtures or with SP only, and this could be attributed to the following: a) Higher fluidity of grout using SP, which enables the grout to fill all the voids between aggregate particles; b) Pozzolanic activity of SF causes acceleration and increase in the hydration rate and products respectively, which in turn leads to enhancement of particle packing density of concrete microstructure. For example, at c/s ratio of 1:0.5 using a combination of SF and SF causes the 28 days strength to be increased by an average percentage of 40% for all w/c ratios considered. On the other hand, increasing the c/s for the same w/c causes an average percentage reduction in strength of 12% at 28 days, which is not a significant value.
Table 3. Compressive strength results of TSC.

| w/c | Type of admixture | Curing Period (days) | Curing Period (days) | Curing Period (days) |
|-----|------------------|----------------------|----------------------|----------------------|
|     |                  | 7 (c/s=1:0.5) | 28 (c/s=1:0.5) | 120 (c/s=1:0.5) | 7 (c/s=1:1) | 28 (c/s=1:1) | 120 (c/s=1:1) | 7 (c/s=1:1.5) | 28 (c/s=1:1.5) | 120 (c/s=1:1.5) |
| 0.45| SF               | 16.79 | 18.49 | 26.59 | 16.60 | 17.35 | 25.65 | 13.58 | 16.22 | 25.09 |
|     | SP               | 12.07 | 18.67 | 20.18 | 13.00 | 17.35 | 19.05 | 15.40 | 15.47 | 17.17 |
|     | SF+SP            | 17.35 | 25.65 | 28.29 | 16.79 | 22.63 | 26.03 | 13.95 | 22.26 | 25.65 |
|     | No admixtures    | 11.13 | 15.28 | 20.37 | 11.13 | 14.15 | 18.11 | 9.24  | 13.00 | 16.03 |
| 0.55| SF               | 13.29 | 15.85 | 24.89 | 11.88 | 15.10 | 20.56 | 10.75 | 13.58 | 19.81 |
|     | SP               | 14.34 | 16.79 | 20.75 | 12.64 | 16.03 | 20.56 | 11.32 | 14.52 | 18.49 |
|     | SF+SP            | 13.20 | 21.32 | 26.88 | 12.83 | 19.24 | 21.50 | 11.70 | 15.00 | 21.87 |
|     | No admixtures    | 8.67  | 12.45 | 15.85 | 8.49  | 9.05  | 13.58 | 7.73  | 8.49  | 12.07 |
| 0.85| SF               | 7.36  | 10.56 | 13.58 | 5.28  | 9.43  | 12.07 | 4.90  | 9.43  | 11.69 |
|     | SP               | 6.98  | 13.20 | 16.22 | 8.11  | 11.51 | 15.47 | 8.86  | 10.94 | 14.52 |
|     | SF+SP            | 9.05  | 14.71 | 16.98 | 9.81  | 11.70 | 15.85 | 10.19 | 11.32 | 15.47 |
|     | No admixtures    | 6.60  | 8.29  | 11.69 | 4.53  | 7.36  | 10.19 | 3.96  | 5.66  | 9.81  |

According to the design algorithm presented in [4, 5], a relationship between compressive strength for (fc`) and w/c ratio has been assumed and presented in Equation 1, as the following:

\[ fc` = A + B \times (w/c) + C \times (w/c)^2 + E \times (c/s) \] (1)

where \( fc` \) represents the estimated compressive strength of TSC, w/c is the water-to-cement ratio and \( c/s \) is the cement-to-sand ratio. Table 4 shows the values of the regression coefficients.

Table 4. Regression coefficients for equation 1.

| Type of admixtures | A      | B      | C      | D      | E      | Correlation Coefficients |
|--------------------|--------|--------|--------|--------|--------|--------------------------|
| SF                 | 23.838 | -19.641| 7.022  | -0.815 | -2.715 | 0.975                    |
| SP                 | -110.44| -172.456| 291.909| 0.418  | -3.823 | 0.947                    |
| SF+SP              | 8.73   | 7.265  | 2.399  | -2.456 | -2.395 | 0.977                    |
| No admixtures      | 7.34   | 5.278  | 1.427  | -2.647 | -3.357 | 0.979                    |

3.2. Tensile strength test results
The splitting tensile strength is commonly used to evaluate the tensile strength of TSC. As shown in table 5, the TSC tensile strength followed a similar trend to that of the compressive strength. The splitting tensile strength at 7 days was low, especially for the mixtures without admixture and then its rate of development increased with time. For instance, the 7-days tensile strength for the mixture incorporating no admixtures was 20 % lower than that of the SF and SP combination mixture. Generally, the higher the TSC compressive strength, the greater the TSC tensile strength was, in agreement with the previous studies [5, 12, 13].
### Table 5. Tensile strength results of TSC.

| w/c | Type of admixture | Curing Period ( days) | Curing Period ( days) | Curing Period ( days) |
|-----|-------------------|-----------------------|-----------------------|-----------------------|
|     |                   | c/s=1: 0.5            | c/s=1:1               | c/s=1:1.5             |
| 0.45| SF                | 2.075                 | 2.248                 | 2.785                 | 1.933                 | 2.357                 | 2.738                 | 1.789                 | 1.982                 | 2.547                 |
|     | SP                | 1.873                 | 2.405                 | 2.783                 | 1.655                 | 1.950                 | 2.542                 | 1.137                 | 1.693                 | 2.167                 |
|     | SF+SP             | 2.452                 | 2.972                 | 3.772                 | 1.982                 | 2.765                 | 2.207                 | 1.796                 | 2.363                 | 3.111                 |
|     | No admixtures     | 1.745                 | 1.837                 | 2.547                 | 1.604                 | 1.673                 | 2.406                 | 1.507                 | 1.603                 | 1.984                 |
| 0.55| SF                | 1.620                 | 1.626                 | 2.359                 | 1.677                 | 1.653                 | 2.078                 | 1.430                 | 1.510                 | 1.698                 |
|     | SP                | 1.666                 | 2.213                 | 2.266                 | 1.636                 | 2.071                 | 2.165                 | 1.415                 | 1.688                 | 2.075                 |
|     | SF+SP             | 1.716                 | 2.122                 | 2.265                 | 1.691                 | 1.839                 | 2.170                 | 1.603                 | 1.608                 | 2.124                 |
|     | No admixtures     | 1.424                 | 1.522                 | 1.768                 | 1.383                 | 1.518                 | 1.628                 | 1.180                 | 1.190                 | 1.579                 |
| 0.85| SF                | 1.226                 | 1.508                 | 1.603                 | 1.037                 | 1.340                 | 1.536                 | 0.713                 | 1.320                 | 1.483                 |
|     | SP                | 0.852                 | 1.450                 | 2.452                 | 1.084                 | 1.320                 | 1.549                 | 1.179                 | 1.320                 | 1.601                 |
|     | SF+SP             | 0.943                 | 1.674                 | 2.304                 | 1.226                 | 1.406                 | 1.699                 | 0.943                 | 1.264                 | 1.625                 |
|     | No admixtures     | 0.884                 | 1.461                 | 1.529                 | 0.870                 | 1.320                 | 1.622                 | 0.578                 | 1.226                 | 1.447                 |

### 3.3. Compressive and tensile strength relationships

The results of this investigation show that there is a good correlation between the compressive strength and tensile strength of TSC. As the compressive strength increased, the tensile strength was also found to increase in the same manner. In the present work, however, the following formula presented in Equation 2 was developed by regression analysis to relate tensile strength (ft) to compressive strength (fc’). The graphical presentation of this relationship is shown in figure 3.

\[
ft = A + B(f_{c'}^*) + C(f_{c'}^*)^D
\]  \hspace{1cm} (2)

where ft is tensile strength and fc’ is compressive strength. Table 6 shows the values of the regression coefficients.

### Table 6. Regression coefficients for equation 2.

| Type of admixtures | A      | B      | C      | D      | Correlation Coefficients |
|-------------------|--------|--------|--------|--------|--------------------------|
| SF                | -6.048 | 0.223  | 26.158 | -0.674 | 0.943                    |
| SP                | -78.020| -0.003 | 75.050 | 0.022  | 0.901                    |
| SF+SP             | 66.074 | 0.584  | -52.448| 0.122  | 0.907                    |
| No admixtures     | -4.197 | 0.249  | 24.023 | -0.871 | 0.936                    |
4. Conclusions

1. As the method of placement in TSC is entirely different from that of NC, using chemical admixtures is necessary to satisfy the requirement for the pumping ability of grout. The superplasticizers were found to be the most suitable admixture in TSC as it enhances the flowability and the passability of the grout and leads to better strength results.

2. The compressive strength of TSC was tested with and without admixture for all grout proportions. On the basis of the results, a correlation between compressive strength and grout proportions was statistically derived.

3. The splitting tensile strength of TSC was investigated for all grout proportions. On the basis of these results, a relationship between tensile and compressive strength of TSC has been statistically derived.

4. The fractured specimens of TSC showed that a large proportion of failures occurred by cracking through the coarse aggregate particles.

5. SF causes acceleration and increase in the hydration rate and products respectively, which in turn leads to enhancing of particle packing density of concrete microstructure.
6. Using SF alone or in combination with SP exhibited better compressive strength results compared to other mixes and this could be attributed the pozzolanic activity of SF.
7. The authors believe that there are many aspects of the failure mechanism of TSC that require clarification through further theoretical and experimental studies. Among them the most notable feature is micro-cracking.

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