Stress-strain behavior of normal and high strength self-compacting concrete

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Abstract. This paper presents an experimental investigation on stress-strain behavior of normal and high strength self-compacting concrete with two different maximum aggregate sizes. Eight mixes are adopted for this purpose with nominal compressive strength ranging from 20 to 80 MPa and maximum aggregate size of 10 and 20 mm. Results show that the ascending parts of the stress-strain curves become steeper as the compressive strength increases and maximum aggregate size decreases. Strain at failure increases with the increase in compressive strength and maximum aggregate size. Also, changing maximum aggregate size from 10 to 20 mm, generally, increases compressive strength (up to 13.97% for cylinders and 17.24% for cubes) and modulus of elasticity (up to 19.27%).

1. Introduction

Self-Compacting Concrete (SCC) is an innovative building material used successfully around the world during the last two decades. It is a highly flowable concrete that can consolidate under its own weight (no additional compaction is needed), spread into formwork without segregation even in the presence of dense reinforcement [1,2,3].

The stress-strain behavior of concrete is dependent on its strength age, rate of loading, cement paste and aggregate properties and size and type of specimens [4,5].

Many researchers have found that the stress-strain relationship of high strength concrete under uniaxial compression differs from that of normal strength concrete by a more linear ascending part to a high percentage of maximum stress, a high strain at maximum stress and the descending part has a steeper slope [6].

Some observations have shown that for equal compressive strength, the elastic modulus of SCC can be as much as 10 to 15% lower than that of conventional concrete of similar compressive strength because of the higher paste content due to the required adjustments of mixture proportions to make SCC, so it is recommended to determine the elastic modulus from trial mixes [1,3].

Since aggregate comprise about 60-80% of concrete mixture volume, it has a significant effect on the strength and behavior of concrete, especially high strength concrete [7]. For SCC, it is recommended that the coarse aggregate content should be 27-36% of the total volume of mixture [2] because the friction between aggregate particles reduces the mixture flowability [1].

The aim of this work is to investigate the stress-strain behavior of normal and high strength SCC (nominal compressive strength ranging from 20-80MPa) with two different maximum aggregate sizes of 10 and 20mm.
2. Experimental Program
Experimental program consists of casting and testing 64 control specimens in addition to tests conducted to evaluate fresh properties. Eight self-compacting concrete mixes are adopted from a large number of trail mixes tested to choose the required properties.

2.1. Materials
The materials used in this investigation are ordinary portland cement satisfying Iraqi standard No.5-1984 [8], fine aggregate (sand) and coarse aggregate (crushed gravel) with nominal maximum size of 10 and 20mm satisfying Iraqi Standard Specification No.45-1984 [9]. Also, limestone powder from local market completely passes the sieve size 0.125 mm with CaO content of 85.3%, and high performance concrete superplasticizer "Glenium 51" are used to produce SCC.

2.2. Mix Proportions
The SCC mixes are prepared according to the Specification and Guidelines for Self-Compacting Concrete (EFNARC 2002) [10] and the European Guidelines for Self-Compacting Concrete (European 2005) [2]. Large numbers of trail mixes were prepared to verify and adjust the properties of fresh concrete as well as hardened concrete.

Also, four levels of compressive strength (20, 40, 60 and 80 MPa) are achieved and eight mixes are made using two different maximum aggregate sizes (10 and 20 mm). Mix proportions of self-compacting concrete are shown in table 1.

| Mix designationa | Mix proportions kg/m³ | SPb l/m³ | W/Pc |
|------------------|-----------------------|----------|------|
|                   | Water    | Cement  | Limestone | Fine aggregate | Coarse aggregate |      |
| M.10.20           | 187.7    | 239     | 311       | 795           | 791            | 4    | 0.34 |
| M.10.40           | 183      | 367     | 195       | 841           | 791            | 4    | 0.31 |
| M.10.60           | 176      | 506     | 86        | 838           | 763            | 6    | 0.29 |
| M.10.80           | 167      | 556     | 30        | 892           | 763            | 7.5  | 0.28 |
| M.20.20           | 195      | 225     | 293       | 749           | 879            | 3    | 0.38 |
| M.20.40           | 182      | 344     | 183       | 795           | 878            | 3.6  | 0.35 |
| M.20.60           | 177      | 485     | 83        | 788           | 878            | 5    | 0.31 |
| M.20.80           | 166      | 556     | 30        | 807           | 879            | 6    | 0.28 |

a M.10.20 = self-compacting concrete with maximum aggregate size of 10 mm and nominal compressive strength of 20 MPa.
b SP = superplasticizer dosage.
c P = cement + limestone.

2.3. Tests of Fresh Concrete

2.3.1. Slump-flow Test. The slump-flow test is performed immediately after mixing according to ASTM C 1611 [11]. This test is the most widely used for evaluating concrete consistency and filling ability in the laboratory as well as at construction sites and can indicates segregation resistance of SCC.

The procedure described below has been followed:
1. The slump cone is placed centrally on the plate, filled with concrete and lifted vertically.
2. The time for the concrete diameter to reach 50 cm (T50) is recorded.
3. When the concrete has stopped flowing, the final diameter of concrete (slump flow) is measured as the average of two perpendicular diameters. Figure 1 shows the slump-flow test.
2.3.2. **L-Box Test.** L-box test is performed according to EFNARC 2002 [10] and European 2005 [2]. Figure 2 shows the L-box test. The procedure described below has been used:

1. The vertical section of the apparatus is filled with concrete which left to stand for 1 minute.
2. The sliding gate is lifted and the concrete is allowed to flow out into the horizontal section.
3. When the concrete stops flowing, the distances "H₁" and "H₂" are measured, and the blocking ratio (H₂ / H₁) is calculated.

![Figure 1. Slump-flow test [12].](image1)

![Figure 2. L-box test [2].](image2)

2.4. **Casting and Curing**

For each mix of SCC, various concrete specimens are casted and cured as follows: three 150×150×150mm cubes and three 150×300mm cylinders for compressive strength, and two 150×300mm cylinders for stress-strain and modulus of elasticity measurements.

All the specimens are cured in water until the time of testing at 28 days.

2.5. **Hardened Concrete Tests**

2.5.1. **Compressive Strength Tests.** Three cubes of 150×150×150mm and three cylinders of 150×300 mm from each mix are casted to determine the compressive strength at the age of 28 days, and an average value is obtained according to BS 1881: part 4:1970 [13] for cube specimens and ASTM C39 [14] for cylinder specimens.

2.5.2. **Strain and Static Modulus of Elasticity Tests.** The longitudinal strain is measured by applying continuous loading at different compressive stress steps (about 1-3 MPa) by a mechanical strain gauge. From the data obtained during the testing of each specimen, the longitudinal stress-strain curves are drawn. The static modulus of elasticity is also obtained in accordance with ASTM C469 [15] as follows:

\[
E_c = \frac{S_2 - S_1}{\varepsilon_2 - 0.000050}
\]

where:

- \(E_c\) = Concrete static modulus of elasticity, GPa.
- \(S_2\) = Stress corresponding to 40% ultimate load, MPa.
- \(S_1\) = Stress corresponding to a longitudinal strain, \(\varepsilon_1\), of 50 millionths, MPa.
- \(\varepsilon_2\) = Longitudinal strain produced by stress \(S_2\).

3. **Results and Discussion**

3.1. **Properties of Fresh Self-Compacting Concrete**
Workability tests are made on fresh concrete immediately after mixing, including slump-flow and L-box. The tests are carried out to determine the flowability, filling ability, passing ability and segregation resistance of SCC.

The results of tests to assess consistency of SCC mixes are illustrated in table 2 with the limits of EFNARC 2002 [10] and European 2005 [2].

### 3.1.1. Slump flow results.
It can be seen from table 2 that as compressive strength increases, slump flow and T\(_{50}\) also increase. Slump flow increasing is a result of higher superplasticizer dosages (with low water-powder ratios) in higher strength concretes, which increase workability and allow concrete to flow further (up to 820 mm diameter) without segregation or bleeding during flowing and after stoppage of the flowing.

Also, higher superplasticizer dosages increase mix viscosity and hence, increase T\(_{50}\) which is an indication to the viscosity of the mix and describes the speed of flow. It is evident that the mix with nominal compressive strength 20MPa can be described as concrete with low viscosity and mixes with nominal compressive strength 40, 60 and 80 MPa can be described as concrete with high viscosity.

### Table 2. Results of fresh self-compacting concrete tests.

| Mix designation | Slump-flow test | L-box test |
|-----------------|-----------------|-----------|
|                 | T\(_{50,cm}\) (sec.) | Slump flow (mm) | H2/H1 |
| M.10.20         | 4               | 645       | 1.0   |
| M.10.40         | 4.13            | 672.5     | 1.0   |
| M.10.60         | 6.02            | 800       | 1.0   |
| M.10.80         | 9.34            | 820       | 1.0   |
| M.20.20         | 2.0             | 585       | 1.0   |
| M.20.40         | 3.5             | 660       | 0.90  |
| M.20.60         | 4.27            | 740       | 0.80  |
| M.20.80         | 5.32            | 750       | 0.75  |
| Limits of EFNARC 2002 [10] | 2-5 | 650-800 | 0.8-1.0 |
| Limits of European 2005 [2] | VS1: ≤ 2, VS2: > 2 | 550-850 | 0.8-1.0 |

Mixes with 20 mm maximum aggregate size (MAS) show lower values for both slump flow and T\(_{50}\) than 10 mm MAS. This is because larger aggregate particles hamper flowing due to their greater mass.

Slump flow values for all mixes lie within the limits (550-850 mm) of European 2005 [2], while some mixes (especially, low viscosity ones) do not conform to the more conservative limits (650-800 mm) of EFNARC 2002 [10]. T\(_{50}\) values for higher strength (higher viscosity) mixes (M.10.60, M.10.80 and M.20.80) are also out of EFNARC 2002 limits (2-5 sec). However, EFNARC 2002 [10] stated that values outside the specified limits may be acceptable under certain circumstances.

In contrast, no acceptance limits for T\(_{50}\) are specified by European 2005 [2]; instead, two viscosity classes expressed by T\(_{50}\) are introduced without upper limits. These classes are: VS1 for T\(_{50}\) ≤ 2 sec (low viscosity SCC) and VS2 for T\(_{50}\) > 2 sec (high viscosity SCC). So, it can be seen that all mixes (except M.20.20) can be classified as VS2 noting that longer T\(_{50}\) may have negative effects like surface finishing difficulties, on the other hand it may be helpful in improving segregation resistance.

### 3.1.2. L-box results.
Mixes with MAS of 10mm have blocking ratio (H\(_2\)/H\(_1\)) of 1.0 which means better flow of concrete than mixes of 20mm MAS whose blocking ratios are generally lower because
the tendency of coarse aggregates blocking (segregation) behind the reinforcing bar is higher for mixes with 20 mm MAS. Similar findings are obtained by Martys and Ferraris (2002) [16] and Daczko (2003) [17].

Blocking ratio for mixes with 20 mm MAS ranges from 1.0 to 0.75 as compressive strength increases due to the slower flow because of the lower water/powder ratios and higher viscosity (increase of superplasticizer dosage) than mixes of 10 mm MAS. Results also show that all mixes (except M.20.80) conform to the limits of both EFNARC 2002 [10] and European 2005 [2]. However, blocking ratio values lower than 0.8 by not more than 0.05 can be accepted according to European 2005 [2].

3.2. Properties of Hardened Concrete

3.2.1. Compressive Strength. The results of compressive strength tests for self-compacting concrete are illustrated in table 3. It is apparent from these results that using higher content of coarse aggregate with 20 mm MAS gives higher compressive strengths than 10 mm MAS for high strength mixes (up to 13.97% for cylinders and 17.24% for cubes), the opposite is observed for normal strength mixes. This behavior may be attributed to the larger aggregate particles contributing to the concrete strength more than smaller ones and this effect is clearly shown in high strength mixes having stronger mortars (and hence, stronger transition zones) where failure may occur through aggregates.

| Mix designation | Cube compressive strength (MPa) | Increasing ratio (%) | Cylinder compressive strength (MPa) | Increasing ratio (%) | Cylinder/cube compressive strength ratio (%) | Modulus of elasticity (GPa) | Increasing ratio (%) |
|-----------------|--------------------------------|----------------------|-----------------------------------|---------------------|-------------------------------------------|--------------------------|---------------------|
| M.10.20         | 26.68                          | -                    | 21.03                             | -                   | 78.82                                     | 25.73                    | -                   |
| M.10.40         | 48.14                          | -                    | 42.06                             | -                   | 87.37                                     | 34.40                    | -                   |
| M.10.60         | 57.42                          | -                    | 51.30                             | -                   | 89.34                                     | 41.66                    | -                   |
| M.10.80         | 73.15                          | -                    | 67.75                             | -                   | 92.63                                     | 45.44                    | -                   |
| M.20.20         | 24.20                          | 9.29                 | 19.43                             | 7.60                | 80.3                                      | 30.69                    | -                   |
| M.20.40         | 53.77                          | +11.69               | 46.40                             | +10.31              | 86.29                                     | 37.71                    | +9.62               |
| M.20.60         | 67.32                          | +17.24               | 58.47                             | +13.97              | 86.85                                     | 42.39                    | +1.75               |
| M.20.80         | 80.65                          | +10.25               | 70.70                             | +4.35               | 87.66                                     | 42.55                    | -6.36               |

In contrast, normal strength mixes having weaker mortars are less dependent on aggregate strength where failure generally occurs in the transition zone between mortar and coarse aggregate which has weaker bond for 20 mm MAS (because of the lower surface area) than 10 mm MAS [18].

Figure 3 shows the relationship between water-powder ratio (w/p) and cube compressive strength. It is clearly shown that compressive strength increases with the decrease in water-powder ratio.

Figure 4 shows the relationship between the cylinder/cube compressive strength ratio and cube compressive strength for self-compacting concrete. It can be seen, that there is a substantial increase in the ratio of cylinder/cube compressive strength with the increase in the cube compressive strength. This can be attributed to the fact that lateral strains (which cause the lower cylinder strength compared to cube) are lower for high strength concrete than normal strength concrete.
3.2.2. Modulus of Elasticity. The results of modulus of elasticity for self-compacting concrete are summarized in table 3. It is clearly seen that, the modulus of elasticity increases with the increase in compressive strength but at a slower rate. The relationship between modulus of elasticity and cube compressive strength is shown in figure 5 and can be expressed by the following equation:

\[ E_c = 7607 f_{cu}^{0.404} \quad (R = 0.928) \]  

Generally, increasing MAS from 10 mm to 20 mm increases modulus of elasticity, which reflects the greater contribution of larger aggregate particles to the stiffness of concrete. Increasing ratio decreases with the increase of compressive strength as shown in figure 6. This indicates that the effect of aggregate stiffness is more evident in mixes with lower mortar strength (stiffness) than mixes with higher mortar strength (stiffness).

3.2.3. Stress-strain Behavior. Figures 7 and 8 show the stress-strain diagrams for self-compacting concrete specimens loaded under uniaxial compressive stresses up to failure. It can be seen that, generally, the ascending parts of the stress-strain curves become more linear as the compressive strength increases.
As shown in figures 7 and 8, the slope of the stress-strain curves tends to increase with the increase in compressive strength. This is because for higher strength concrete, high quality and dense cement paste can be achieved with a less tendency for internal microcracking.

Strain at failure increases with the increase in compressive strength and ranges from 0.8 to 2.38 mm/m.
Figures 9 to 12 show the effect of MAS on stress-strain curves for nominal compressive strengths of 20, 40, 60 and 80 MPa, respectively. As shown in these figures, mixes with 10 mm MAS have generally stiffer response than mixes with 20 mm MAS. This may be attributed to the better bond of cement paste with smaller aggregate particles and hence, stronger transition zone which delay the occurrence of transition zone microcracks. However; near failure, stress-strain curves for mixes with 20 mm MAS, approach those for 10 mm MAS as the contribution of larger aggregate particles becomes more effective.

4. Conclusions

Based on the results of this work, the following conclusions can be drawn:

1. Slump flow and T50 values of self-compacting concrete increase with the increase of compressive strength as a result of higher superplasticizer dosages (with low water-powder ratios) in higher strength concretes which increase workability as well as viscosity and allow concrete to flow further (up to 820 mm flow diameter) but slower without segregation or bleeding during flowing and after stoppage of the flowing.
2. The tendency of coarse aggregates blocking (segregation) is higher for mixes with 20 mm maximum aggregate size than those with 10 mm maximum aggregate size.
3. Using higher content of coarse aggregate with 20 mm MAS gives higher compressive strengths than 10 mm MAS for high strength mixes (up to 13.97% for cylinders and 17.24% for cubes). This behavior may be attributed to the larger aggregate particles contributing to the concrete strength more than smaller ones and this effect is clearly shown in high strength mixes having stronger mortars (and hence, stronger transition zones) where failure may occur through aggregates.
4. The modulus of elasticity increases with the increase in compressive strength but at a slower rate.
5. Generally, increasing maximum aggregate size from 10 mm to 20 mm in SCC increases modulus of elasticity (upto 19.27%), which reflects the greater contribution of larger aggregate particles to the stiffness of concrete. Increasing ratio decreases with the increase of compressive strength. This indicates that the effect of aggregate stiffness is more evident in mixes with lower mortar strength (stiffness) than mixes with higher mortar strength (stiffness).
6. The slope of the stress-strain curves tends to increase with the increase in compressive strength. This is because for higher strengths, high quality and dense cement paste can be achieved with a less tendency for internal microcracking.
7. Stress-strain curve of mixes with 10 mm MAS have generally stiffer response than mixes with 20 mm MAS. This may be attributed to the better bond of cement paste with smaller aggregate particles and hence, stronger transition zone which delay the occurrence of transition zone microcracks.

8. Strain at failure increases with the increase in compressive strength and ranges from 0.8 mm/m to 2.38 mm/m.

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