Self-compacting grout to produce two-stage concrete

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Abstract
Traditional concrete (TC) is primarily composed of a mixture of cement, fine and coarse aggregates, and water. TC is made by mixing together all the components before placing them. Using non-traditional concrete (two-stage concrete) to solve and to eliminate the problem of the aggregate segregation which appears in TC and in the self-compacting concrete. Two-stage concrete (TSC) consists of two main components, namely the grout and coarse aggregate particles. Coarse aggregates are placed into the formwork, and then a fresh grout mixture is injected into the formwork to fill the voids created by the coarse aggregates. The main difference between TC and TSC is the method of preparation and size of aggregates. The described above technology is unique as it allows us to prevent aggregate segregation in a ready mixture. This paper presents the experimental results of preplaced, crushed granite aggregate concreted with five different grout mixture proportions. A total of 48 concrete cylinders were tested in unconfined compression and splitting tension at 28 and 90 days. It was found that splitting tensile strength of the TSC is equivalent or higher than that of TC at the same compressive strength. Splitting tensile strength can be conservatively estimated using the ACI equation for traditional concrete.

Keywords: Two-stage concrete (TSC); self-compacting grout (SCG); segregation; lightweight concrete; heavyweight concrete.

1. Introduction

Two-stage concrete (TSC), also known as preplaced aggregate concrete, is produced by first placing the dry coarse aggregate in the formwork and then filling the interparticle voids with a flowable grout mixture as shown in Figure 1, [1-3]. Generally, the properties of TSC are thus influenced by the properties of the coarse aggregate, the properties of the grout, and the effectiveness of the grouting process [4-6]. When placed properly, TSC has beneficial properties such as low drying shrinkage, high bonding strength, high modulus of elasticity, and excellent durability [7]. The method of TSC has proved particularly useful in a number of applications like underwater construction, and masonry repair, where placement by conventional methods is extremely difficult. The method is also applicable in case of massive concrete where low heat of hydration is required [8-9]. Presented by [10] two case studies of high-density concrete using TSC where modulus of rupture was measured, it was found that the modulus of rupture is 11-13% of the unconfined compressive strength and is consistent with the expectations of flexural strength of TC. The author of [11] presents two different methods of lightweight concrete (LC) including a preplaced lightweight aggregate concrete (PLC) and conventional lightweight concrete (CLC). Their results show that the mechanical properties of PLC are improved with respect to that of CLC of the same mixture. The increase of shrinkage is approximately 13% for CLC and 6% for PLC due to the effect on interlocking. PLC shows an increased tendency in elastic modulus by approximately 3.3% compared with CLC [12-14]. The objective of this paper was to study the strength of TSC in compression and tension at 28 and 90 days using different grout mixtures.

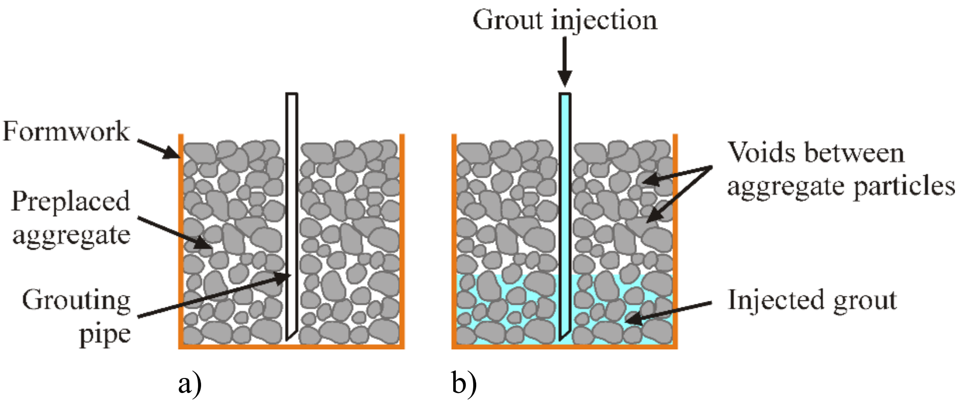

Figure 1. a) Coarse aggregate placement and b) grout pumping through pipes.

2. Materials

2.1. Coarse aggregate

The coarse aggregate used in these experiments was subangular granite. A large sample was acquired, washed, and sieved to create gradation with a maximum size of 50 mm. The coarse aggregate had a bulk dry specific gravity of 2.629, absorption of 0.51%, and Los Angeles abrasion of 24%. Because of its low absorption and high abrasion resistance, this granite is considered a high-quality coarse aggregate.

2.2. Grout

In this investigation, a simple grout with no admixtures was used. Fine aggregate, used in it, was produced from silica sand, which is subangular in shape with 100 percent passing a 2.36 mm. The sand has an absorption of 0.63% and was mixed in a moist state at an average moisture content of 3.02%. The cement used throughout the experiments was ordinary (Type I) Portland cement.

3. Grout mixture proportioning and concrete specimen preparation

The selection of water-cement-sand ratios is more critical in TSC because the amounts of sand and water control the pumpability of grout, an essential requirement in the production of TSC [15]. The coarse aggregate was first placed in 150 x 300 mm hard plastic cylindrical moulds. The void content of the preplaced aggregate ranged from 48 to 51% and the bulk density ranged from 1298 to 1394 kg/m^3. Five different proportions of water to cement (0.42, 0.45, 0.50, 0.55 and 0.65) were investigated with a constant 1:1 ratio of cement to sand. Trials were made with grout to find the minimum water-to-cement (w/c) ratio at which the preplaced aggregate could be effectively grouted. A w/c ratio of 0.45 was established to be the minimum ratio suitable for grouting; it was not possible to penetrate all voids in the aggregate skeleton with grout at a w/c ratio of 0.42 Figure 2.

Figure 2. Shown grout was not able to fill all the voids in the aggregate skeleton.

4. Experimental Program

The experimental program consisted of a series of unconfined compression tests and splitting tensile tests on cylinders prepared from different grout mixtures at the ages of 28 and 90 days. To effectively compare the unconfined compressive strength to tensile strength, it was determined that both tests should be conducted using 150 x 300 mm cylindrical specimens prepared in the same manner. Excluding the specimens at a w/c ratio of 0.42, there were 48 concrete specimens tested. Three specimens from each of the four grout mixtures were tested in unconfined compression and split in tension at two different ages. After one day of casting the concrete specimens were removed from the cylinders and covered with moist burlap for seven days and stored in the laboratory climate.

4.1. Experimental Test Procedures

Grout cubes were prepared and tested in unconfined compression per ASTM C 942. Three cubes of each grout were tested at 28 and 90 days. Unconfined compression tests on TSC cylinders were tested in accordance with ASTM C 39. Three specimens of each concrete cylinders were tested at 28 and 90 days. Splitting tensile tests were also conducted on three specimens of each concrete mix at 28 and 90 days. according to the procedures outlined in ASTM C 496. The splitting tensile strength is calculated using equation (1) as follows:

$$f_s = 2P/(\pi L D) \qquad (1)$$

where: f_s - splitting tensile strength (MPa), P - maximum applied load (kN), L - specimen length (mm), D - specimen diameter (mm).

5. Results and discussion

5.1. Compressive strength

The unconfined compressive strength of TSC was measured at 28 and 90 days. Figure 3 shows the mean and individual strengths of three specimens per water to cement (w/c) ratio at 28 days. It can be seen that the average compressive strength of 31.9 is attainable at 28 days with a w/c ratio of 0.45. Figure 3 demonstrates a strength reduction as the w/c ratio increases. Although there is some variation in strength measured per w/c ratio, the strength reduction is approximately linear. This observation is consistent with the unconfined compressive strength measurements of TSC cube specimens (300 x 300 x 300 mm^3), where Abdelgader [5] determined the relationship between compressive strength and w/c ratio and c/s of TSC at 28 days as:

$$\bar{f_c} = 62.08 - 71.00 \cdot (^{W}/_{C}) + 0.52 \cdot (^{C}/_{S}) \qquad (2)$$

Where: $f_c^{'}$ compressive strength (MPa), w/c- water to cement ratio and c/s- cement to sand ratio.

Equation (2) is illustrated in Figure 3 for cement to sand (c/s) ratio of 1.0, and it can be seen that it under-predicts the strength of the cylindrical specimens tested in this program. The predicted mean strength from equation (2) is 87 to 93% of the measured mean strength. Decreasing the multiplicative factor on the w/c ratio in equation (2) to account for cylindrical specimens yields the following relationship:

$$\bar{f_c} = 62.08 - 68.00 \cdot (^{W}/_{C}) + 0.52 \cdot (^{C}/_{S}) \qquad (3)$$

Where c/s = 1.0 for specimens investigated herein. Further research is required to determine the suitability of the equation (3) for a range of c/s ratios. Another significant finding from the compressive strength data was the somewhat limited rate of strength development. This can be explained, in part, because of the fact that no-fly ash or other pozzolans were incorporated in the cement grout. Compressive strength data shown in Table 1 reveal that the mean 90-day strengths are higher than the mean 28-day strengths. The percent increase ranges from 5 to 17%, where concrete with a w/c ratio of 0.65 demonstrated the largest strength gain from 17.4 to 20.4 MPa. These observations show that, although the mechanism of stress transfer is believed to be different from the one of conventional concrete, the grout strength is a controlling factor in the strength of TSC. To this end, Table 1 quantifies the impact of grout strength on TSC strength. The table summarizes the mean and range of compressive strength of the grout and concrete at 28 and 90 days. It can be seen that the range of measured compressive strengths at 28 days are sometimes high for both grout and concrete. Variability in the data can be simply expressed by the range-to-mean percentage, which calculates from 12 to 31% for concrete at 28 days. However, the variability in compressive strength measurements at 90 days reduces to less than 12% for grout and concrete.

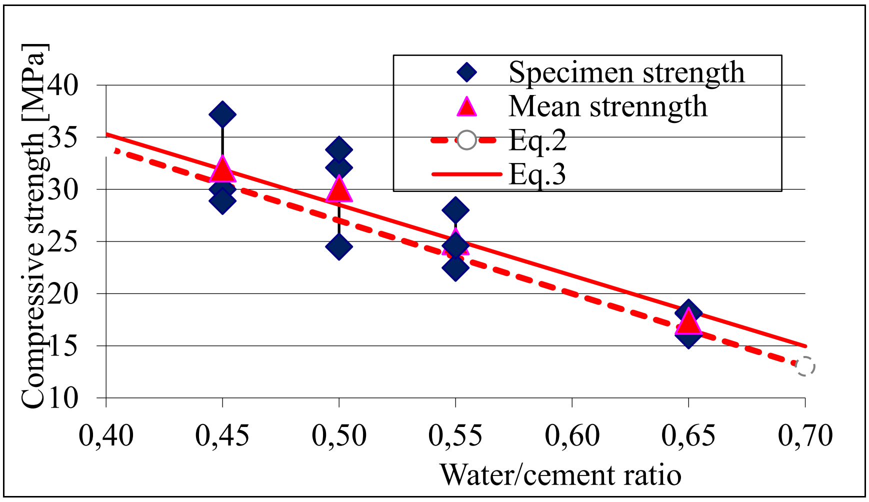

Figure 3. 28 days compressive strength vs. water-cement ratio.

Table 1. Compressive strength of grout and concrete at 28 and 90 days.

w/c ratio	28 days grout compressive strength (MPa)		28 days concrete compressive strength (MPa)		concrete: grout mean strength ratio
	mean	range	mean	range	
0.45	63.1	1.9	31.9	7.4	0.51
0.50	60.3	15.2	30.0	9.2	0.50
0.55	49.8	3.0	25.1	6.5	0.50
0.65	31.2	12.1	17.4	2.1	0.56
w/c ratio	**90 days grout compressive strength (MPa)**		**90 days concrete compressive strength (MPa)**		**concrete: grout mean strength ratio**
	mean	range	mean	range	
0.45	67.9	2.3	33.4	2.8	0.49
0.50	57.6	4.5	34.2	3.9	0.59
0.55	48.5	1.6	26.4	2.6	0.54
0.65	36.4	3.5	20.4	1.0	0.56

5.2. Tensile strength

The splitting tensile strength of TSC was also measured at the 28 and 90 days. Figure 4 shows the mean strengths of three specimens per w/c ratio at the ages of 28 and 90 days, respectively. The results indicate that a strength reduction as the w/c ratio increases. However, there appears to be little difference in strength between specimens produced with a w/c ratio of 0.45 and those produced with a w/c ratio of 0.50. This was also observed with the compressive strengths measured for the same grout mixtures. More importantly, there appears to be almost no increase in tensile strength from 28 to 90 days for all mixtures. The actual values of tensile strength at w/c ratios of 0.45 and 0.50 measured from 3.1 to 3.3 MPa, which indicates satisfactory results, especially when one considers the minimum cost of concreting and that no vibration tools are used. Furthermore, excellent results can be expected even when using a high w/c ratio of 0.65, where the mean tensile strength is nearly 2.5 MPa. Test observations show that failure in splitting tension was restricted principally to the line of split and occurs through the grout and coarse aggregate.

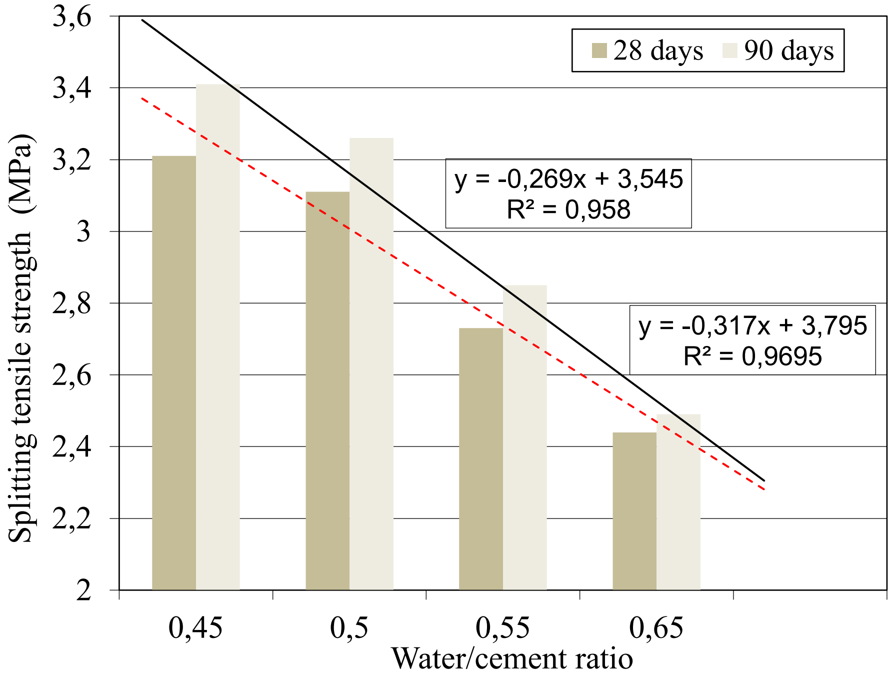

Figure 4. Mean splitting tensile strength vs. w/c ratio at the ages of 28 and 90 days.

5.3. Compressive-tensile strength relationship

The results of this investigation show that the splitting tensile strength of TSC can be approximated well by the ACI equation for conventional concrete, as shown in Figure 5. For conventional concrete, the predictive equation is given by equation (4):

$$f_s = 0.56\sqrt{f_c'} \tag{4}$$

Where: f_s-splitting tensile strength (MPa), and f_c' compressive strength (MPa). In this investigation, the splitting tensile strengths can be estimated as given in equation (5):

$$f_s = (0.55 \div 0{,}58)\sqrt{f_c'} \tag{5}$$

Equation (5) conforms closely to the ACI equation (4) is also valid for estimating 90-day splitting tensile strengths based on 90-day compressive strengths, as the data in Figure 5 suggest. In this investigation, the factor in equation (4) ranges from 0.52 to 0.56 for 90-day strengths. Figure 5 includes compressive and splitting tensile strength results from a concurrent investigation by Abdelgader [15]. In that investigation, 150 mm x 300 mm concrete cylinders were produced with a similar grout mixture (w/c ratios of 0.45, 0.50, 0.55 and 0.60 at a c/s ratio of 1.0). The coarse aggregate source was a crushed dolomitic limestone from Tarhuna, located 65 km south of Tripoli, Libya. Particles were subangular in shape and the gradation was uniform, with a maximum size of 50 mm. The physical characteristics of that limestone and this granite are quite similar, but the results show a higher splitting tensile strength for TSC produced by limestone. The splitting tensile strengths can be estimated as shown in equation (6):

$$f_s = (0.63 \div 0{,}68)\sqrt{f_c'} \quad (6)$$

The data from both studies show that the splitting tensile strength of TSC is at least as high as that of conventional concrete and, in fact, it can be higher depending on the selection and properties of the coarse aggregate. The greater mechanical interlocking among particles in TSC could be responsible for the higher tensile strength since factors like aggregate gradation are different from conventional concrete. These observations give a possibility of a much deeper investigation into the influence of coarse aggregate properties on TSC behavior in tension.

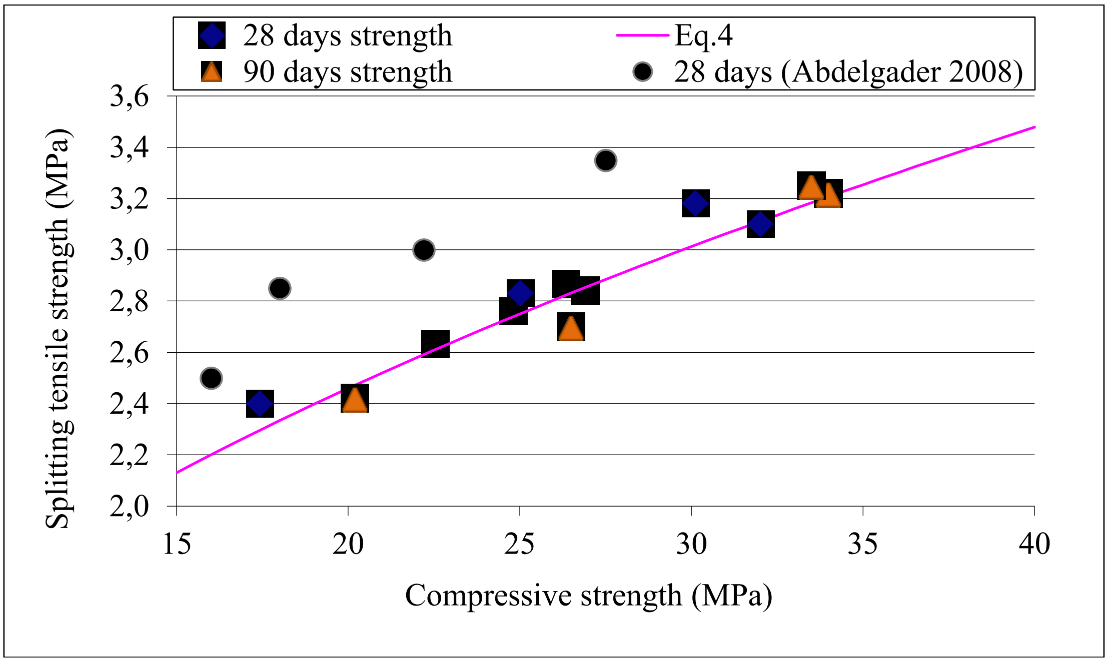

Figure 5. Mean splitting tensile strength vs. mean compressive strength.

6. Conclusions and recommendations

The following conclusions can be drawn from this study:

1. A grout mixture with a water-to-cement (w/c) ratio of 0.45 to 0.50 and a cement-to-sand ratio of 1.0 optimizes the compressive and tensile strength of TSC. Grout mixed with a w/c ratio below 0.42 is too viscous and does not fully penetrate the voids between coarse aggregate particles and therefore, creates a honeycombing effect in the hardened concrete. No superplasticizer has been used for the grout.
2. When mixed with a simple grout, the mean compressive strength of TSC increases by 5 to 17% between 28 and 90 days. In this investigation, a maximum compressive strength of 34.2 MPa at 90 days was achieved. Long-term strength gain may have been limited by the fact that no-fly ash or other pozzolans were incorporated in the grout.
3. The splitting tensile strength of TSC was found to be similar to that predicted by the ACI equation for splitting tensile strength of conventional concrete. In some cases, the measured tensile strength of TSC and in fact higher than that predicted by the

ACI equation. However, there was no observable increase in tensile strength between 28 and 90 days.

4. Coarse aggregate particles are in close contact before and after grouting, it seems that the strength of coarse aggregate plays an important role in the development of its compressive strength. To develop a correlation between the strength of coarse aggregate and the strength of concrete it is necessary to test TSC with aggregates of different strength.

Above all, the method of TSC provides a better solution for the segregation problem in concrete. TSC does not need vibration to achieve a denser structure, which can in turn contribute to cost-cutting in practice.

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