Third International Conference on Sustainable Construction Materials and Technologies http://www.claisse.info/Proceedings.htm

Flexural Strength of Two-Stage Concrete

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ABSTRACT

Two-stage concrete (TSC) acts fundamentally in a different way under external stress to traditional concrete where the concrete matrix absorbs, distributes and resists the stresses. Due to point-to-point contact in TSC all the stress is passed first through the stone skeleton then, after deformation of the stone particles, the grout both restrains the aggregate and transfers the loads. This paper presents an out-put results from a comprehensive research conducted to study the flexural strength of TSC using local materials of Libya. 16 mixes were prepared and tested at 28 days of normal curing, having water /cement ratio (w/c) of, 0.55, 0.65, 0.75 and 0.80 and sand/cement ratio (s/c) of 1, 1.25, 1.5 and 2.0. Empirical relationships between concrete mix components and both compressive strength and modulus of rupture were developed and demonstrated, in addition the results were compared with American concrete institute (ACI) code equations.

Keywords. Flexural Strength, Mixture Proportioning, Compressive Strength, Modulus of Rupture, Two-Stage Concrete.

INTRODUCTION

Two-stage concrete (TSC) is a simple concept; it is made using the same basic constituents as traditional concrete. As the name would suggest it is produced through a two-stage process. Firstly washed coarse aggregate is placed into the formwork in-situ. 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 (ACI Committee 304, 1992). Specific admixtures can be chosen as the need arises to improve strength, bond and physical characteristics. The TSC may be regarded as a skeleton concrete because the aggregates rest one on another and only the remaining voids are filled with grout (Abdelgader, 1996), whereas in normal concrete the aggregates are rather dispersed. This is also the reason why, contrary to the ordinary concrete, the TSC should not be described as an isotropic material. The exceptionally high proportion of coarse aggregate in TSC, up to 70% when using a blended mixture of two or more aggregate sizes, results in the use of less cement paste and gives lower overall shrinkage and greater economy than traditional concrete (Warner, 2005). Mechanically TSC acts in a fundamentally different way under external stress to traditional concrete where the concrete matrix absorbs, distributes and resists the stresses. Due to the point-to-point contact between aggregate particles all the stress is passed first through the stone skeleton then, after deformation of the stone particles, the grout both restrains the aggregate and transfers the loads (Nowek, Kaszubski, Abdelgader, and Gorski, 2007). Mechanical properties of TSC are thus influenced by the properties of the coarse aggregate, the properties of the grout (Swaddiwudhipong, Zhang, and Lee, 2002), and the effectiveness of the grouting process (Abdul Awad, 1988; Abdelgader, 1999). While the mechanical properties of TSC in compression have been well documented, there remains little published data on tensile and flexural strength (Abdelgader, and Górski, 2003).

This paper presents an out-put results from a comprehensive research conducted to study the flexural strength of TSC using local materials of Libya (Abdurrahman, 2007). Empirical relationships between concrete mix components and both compressive strength and modulus of rupture were developed and demonstrated, in addition the results were compared with ACI code equation.

EXPERIMENTAL PROGRAM

Materials used. Ordinary Portland cement was used in all mixes though out this research. The cement properties were tested according to British standards (British Standard Institution, 1991). Its physical and mechanical properties are presented in Table 1.

Table 1. Physical and mechanical properties of cement paste

Property	Value
Standard Consistency	24.2%
Initial Setting Time	2:05 hours
Final Setting Time	4:10 Hours
Fineness	3497 cm^2/g
Soundness	1.5 mm
Compressive strength (3 Days)	23 N/mm^2
Compressive strength (7 Days)	33.5 N/mm^2
Compressive strength (28 Days)	42 N/mm^2

Two angular aggregates of maximum sizes 20 and 37.4 mm were used and blended with a ratio of 2:1 respectively. Tests were carried out to check the coarse aggregate suitability according to according to British standards (British Standard Institution BS-882, and BS-812, 1985). These tests indicates that the coarse aggregates has a specific gravity of 2.65, absorption of 1.66%, unit weigh of 1685 Kg/m^3 , and both crushing value and impact value of 18.85% and 21.26 % respectively. The grading curves of the blended aggregates are illustrated in Figure 1.The fine aggregate that was used in the grout mixture was natural beach sand imported from the Zletin quarry (about 150 km East of Tripoli city), has a size not exceeding 2 mm, fineness modulus of 1.4, absorption of 0.14%, and a specific gravity of 2.62. Grading curves are presented in Figure 2. Quality control tests were also conducted to check its properties according to the British standards (British Standard Institution BS-882, and BS-812, 1985).

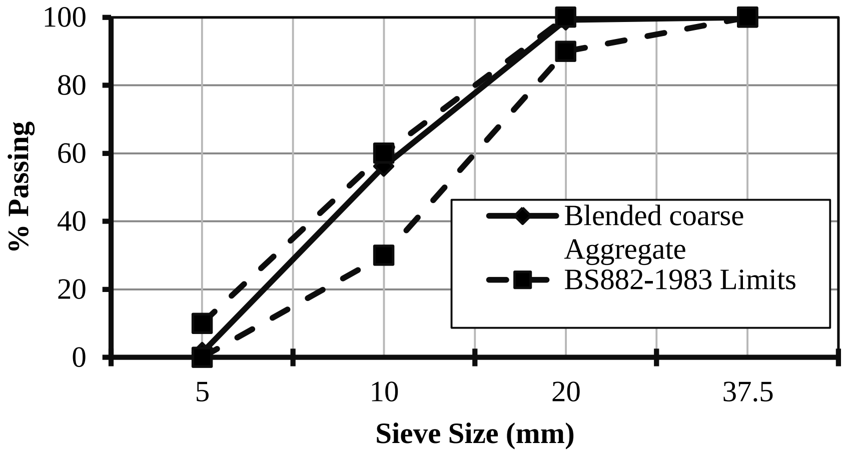

Figure 1.Sieve analysis of blended coarse aggregate

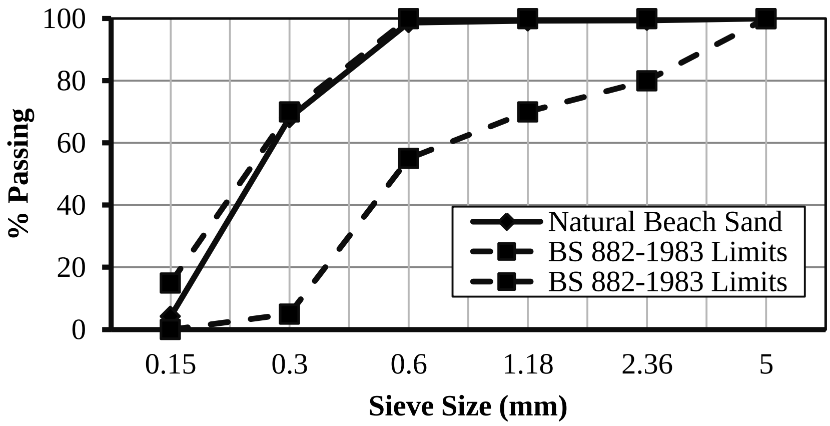

Figure 2.Sieve analysis of fine aggregate (natural beach sand**)**

Water used is a fresh, dirt-free water, with a percentage of total dissolved salts not exceeding 2,000 particles per million as specified by British standards (British Standard Institution BS-3148, 1985).

Design of concrete mixes. The American Concrete Institute (ACI) method was used during this research to obtain the mixtures proportions. Both flow cone and flow table tests were conducted to characterize the grout for fluidity and propagation ability. Based on a previous preliminary investigations conducted by the authors and others (Abdelgader, and Elgalhud, 2008) to design suitable TSC mixes using local materials, sixteen mixes designed and implemented having w/c ratio of: 0.55, 0.65, 0.75 and 0.8 ; s/c ratio of : 1.0, 1.25,1.5 and 2.0. The volume of free spaces between coarse aggregate grains (void ratio, e) was also determined and an average value of 45% was used through-out this research. Table 2 presents the contents of all the mixes investigated.

Table 2.Grout Mix Proportions

Mix No.	Water/cement ratio (w/c)	Sand/cement ratio (s/c)	Cement	Sand	Water
			Kg/m^3		
1	0.55	1.00	360	198	360
2	0.65		333	183	333
3	0.75		310	170	310
4	0.80		300	165	300
5	0.55	1.25	334	184	418
6	0.65		311	202	389
7	0.75		291	218	364
8	0.80		282	225	352
9	0.55	1.50	312	171	468
10	0.65		292	189	438
11	0.75		274	205	411
12	0.80		266	213	399
13	0.55	2.00	275	151	551
14	0.65		259	168	519
15	0.75		245	184	491
16	0.80		239	191	478

Mixing procedure. All Concrete batches were prepared in a table paddle-type mixer having a capacity of 0.003m^3. First, sand and cement are introduced and mixed on dry condition for not less than 2 minutes to ensure the homogeneity of the blend. Second, water added carefully and slowly to the mixer, and the mixing continued for other three minutes.

Test specimens preparations and curing. Compressive and flexural strength of TSC were investigated using standard cubes of size 150x150x150 mm and standard beams of size 150x150x750 mm respectively. Grout strength was taken as an extra indication of strength and measured using standard cubes of size 100x100x100 mm. A total of 192 samples were casted in an average of 12 samples per mix. Moulds had been cleaned and oiled to facilitate easy demoulding and filled first by saturated surface dry aggregate before introducing the grout. The grout was delivered into the preplaced aggregate skeleton under gravity pressure to produce the TSC through hard plastic injection pipe having a diameter of 20mm and a height of 2 meters. The pipe is lowered to the bottom of the samples and then drawn up when the grout fill the voids in the aggregate Skelton. After 24 hours of the casting process, the concrete samples were removed from the moulds and then immersed in a water tank for seven days. All specimens were then removed from water curing tanks and stored in the laboratory air at 25 C^0 until testing age at 28 days.

Fresh concrete investigations. Once, the mixing process completed the workability tests were performed in quick succession. In order to measure the discharging time of known volume of concrete and propagation capacity of the grout, typically, V-funnel and flow-table tests were conducted according to American standards (ASTM, 2001;Abdurrahman, 2007). Table 3 presents sample of fluidity results of. From The results it is clear that as s/c ratio and w/c ratio increased a considerable reduction of filling time was noticed and vice-versa for flow meter test results.

Table 3.Sample of fluidity results

Water/cement ratio (w/c)	Sand/cement ratio (s/c)	Fluidity	
		Flow cone (Sec.)	Flow meter (cm)
0.55	1.00	94	8
		90	9
0.80	2.00	40	15
		37	16

Hardened concrete investigations. Flexural strength and compressive strength of both TSC and grout at the age of 28 days were investigated using a universal hydraulic testing machine with maximum capacity of 2200 KN. The rate of loading was approximately adjusted at 0.5 KN/sec and 0.05 KN/sec for compressive strength and flexural strength respectively. The test results are calculated as the mean of four samples per each mix as presented in Table 4. Flexural strength of TSC will be discussed in the next subtitles.

FLEXURAL STRENGTH INVESTIGATIONS

The flexural strength investigation was performed according to the requirement of British standards (British Standard Institution BS-1881: part 118, 1983), as shown in Figure 3.Flexural strength in terms of modulus of rupture (f_r) was investigated, using the failure load of beams (P) as shown in equation-1-. Since there is no equation for calculating Modulus of rupture theoretically in TSC we use ACI code expression for normal concrete as shown in equation 2, (ACI building code, 2008).

$$f_r = \frac{MxY}{I} = \frac{PL}{bh^2} \quad \text{(MPa)} \quad [1]$$

$$f_r = 0.62x\sqrt[2]{f_c'} \quad \text{(MPa)} \quad [2]$$

Where: L is the span length, b is the cross section width, h is the section height, and fc` is the compressive strength of concrete.

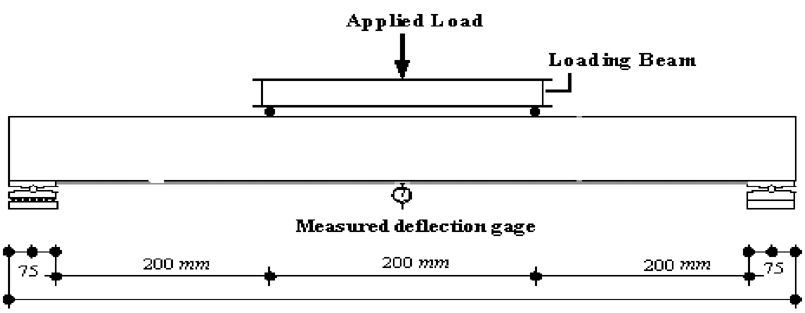

Figure 3. Test setup for flexural strength

Table 4.Compressive and flexural strength test results

Mix No.	Water/cement ratio (w/c)	Sand/cement ratio (s/c)	Compressive strength (fc')*		Flexural strength (f_r)
			TSC	Grout	TSC
			N/mm^2		
1	0.55	1.00	26.23	33.00	2.62
2	0.65		16.89	34.00	2.70
3	0.75		17.56	26.50	2.21
4	0.80		14.89	28.00	2.01
5	0.55	1.25	20.00	38.00	2.99
6	0.65		20.89	29.00	2.64
7	0.75		19.78	27.00	2.54
8	0.80		13.78	28.00	2.12
9	0.55	1.50	20.11	**	**
10	0.65		24.00	43.00	3.18
11	0.75		19.78	34.00	2.15
12	0.80		12.44	29.50	2.20
13	0.55	2.00	**	**	**
14	0.65		24.67	33.00	2.68
15	0.75		16.89	40.00	2.12
16	0.80		18.00	34.00	1.68

* Average of four samples ** No flowability

DISCUSSION OF RESULTS

Effect of w/c and s/c ratio. Although, the flexural strength of concrete is very sensitive, the impact of both w/c and s/c ratios on this property for TSC were studied in this paper. It is clear as shown in Figure 4 that the trend of results showed that for the same w/c ratio it seems that the effect of s/c ratio is not significant specially for values of w/c equal or greater than 0.65. This may be related to the variation in the ability of the grout to propagate and fill the voids in the aggregate Skelton, and this ability is not possible for low w/c (i.e. w/c=0.55). This observation also consistent with compressive strength results as shown in Table 4. From the experimental data presented it is clear that the best results approximately obtained using w/c and s/c of 0.65 and 1.25 respectively.These observations show that, although the mechanism of stress transfer is believed to be different from conventional concrete, the mortar strength is a controlling factor in the strength of two-stage concrete. 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. This observation suggests that the compressive strength of two-stage concrete can be conservatively estimated as one-half of its mortar strength. If this ratio can be substantiated with more mixtures and other sources of coarse aggregate, this simple rule-of-thumb can be adopted in the design of two-stage concrete.

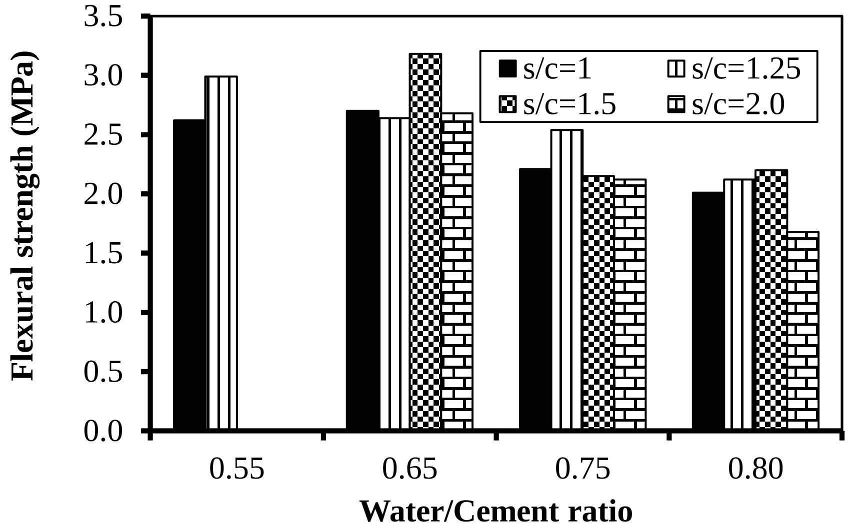

Figure 4. Effect of both w/c and s/c ratio on measured flexural strength of TSC

Regardless of results variations the statistical analysis using Iteration technique with modern computer technology showed that an empirical equations with excellent correlation coefficients (R^2) could be obtained to relate flexural strength of TSC with either w/c or s/c as shown in Table 5. Also, a general equations to relate compressive strength and flexural with both w/c and s/c ratio are presented in equations 3&4. Graphical demonstration of modulus of rupture using equation 3 is also shown in Figure 5.

$$fr = -10.22 + 32.34\,(w/c) + 5.05\,(s/c) - 26.55\,(w/c)^2 - 1.82\,(s/c)^2 \qquad \text{(MPa)} \quad [3]$$

$$fc` = -26.2803 + 183.95(w/c) - 8.44(s/c) - 158.53(w/c)^2 + 3.51(s/c)^2 \qquad \text{(MPa)} \quad [4]$$

It was found that an optimum values of both w/c and s/c ratio could be obtained by differentiating equations 3 and 4. Values of w/c and s/c ratio of 0.6 and 1.3 respectively were found the optimum. These theoretical results are highly consistent with the experimental results as discussed previously in this section.

Table 5.Flexural strength model relationships

w/c	(f_r& s/c) Model relationships (MPa)	R^2
0.55	$f_r = 1.16 + 1.46(s/c)$	0.16347
0.65	$f_r = 13.62 - 24.65(s/c) + 18.23(s/c)^2 - 4.36(s/c)^3$	0.84431
0.75	$f_r = -32.82 + 75.87(s/c) - 52.17(s/c)^2 + 11.46(s/c)^3$	0.93813
0.80	$f_r = -6.04 + 15.89(s/c) - 10.03(s/c)^2 + 1.99(s/c)^3$	0.87014
s/c	(f_r& w/c) Model relationships (MPa)	R^2
1	$f_r = 28.69 - 131.73(w/c) + 223.01(w/c)^2 - 125.41(w/c)^3$	0.96882
1.25	$f_r = 153.69 - 690.28(w/c) + 1046.04(w/c)^2 - 525.04(w/c)^3$	0.96602
1.5	$f_r = 8.14 - 9.16(w/c) + 1.78(w/c)^2$	0.99303
2.0	$f_r = -4.12 + 22.28(w/c) - 18.96(w/c)^2$	0.92693

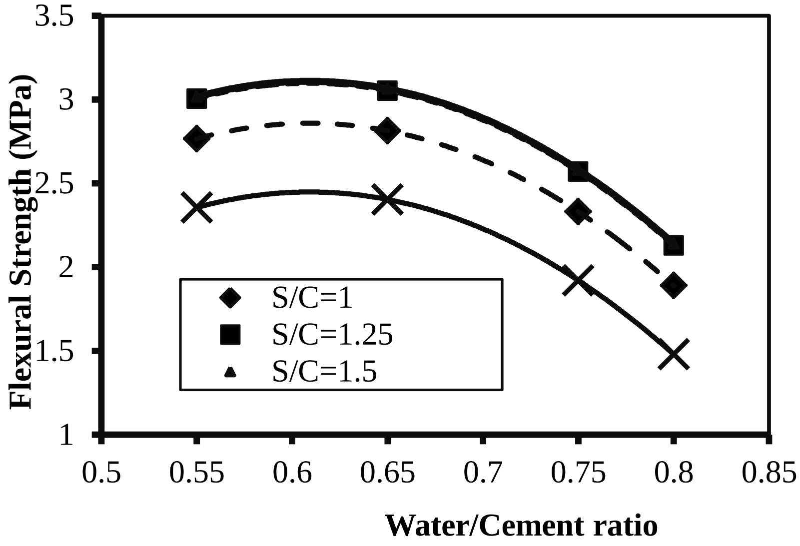

Figure 5. Calculated flexural strength of TSC using experimental data models

Comparison of experimental data with ACI code equation. The results of this investigation show that the modulus of rupture (f_r) of two-stage concrete can be approximated well by the ACI equation for conventional concrete, as shown in Figure 6. From the test results during this research it was found using the statistical analysis that the best correlation equation between compressive strength ($f_{c'}$) and modulus of rupture (f_r) is presented in equation 5 as follows.

$$f_r = 0.56x\sqrt[2]{f_c'} \quad \text{(MPa)} \qquad [5]$$

Calculated modulus of rupture using the ACI code equation as presented in equation 2 is also used to compare with corresponding experimental values using equation 5. In general, the values from both equations are close and the difference does not exceed 10%as presented in Figure 6.The data from study show that the flexural strength of two-stage concrete 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. No causes were apparent for the relatively higher flexural strength in two-stage concrete. However, the greater mechanical interlocking among particles in two-stage concrete could be responsible for the higher flexural strength since factors like aggregate gradation are different from conventional concrete. These observations warrant a much deeper investigation into the influence of coarse aggregate properties on two-stage concrete behavior in flexural.

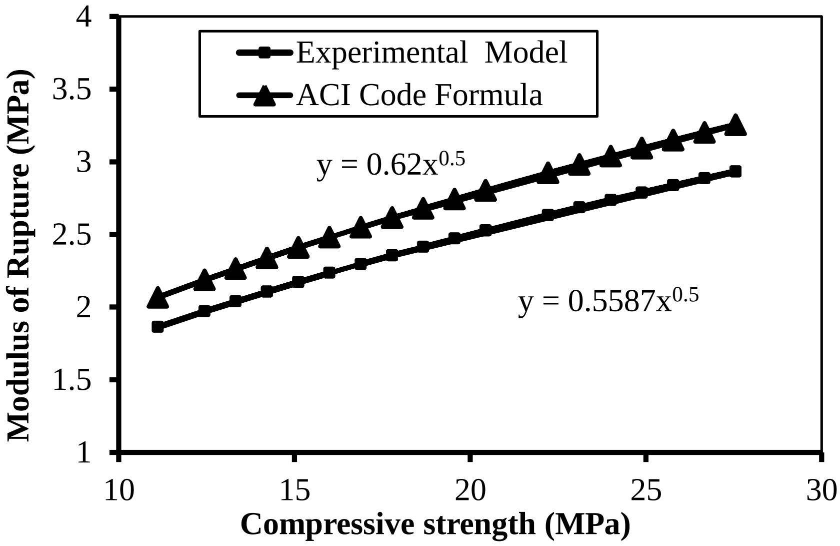

Figure 6. Modulus of rupture using experimental data model verses ACI code equation

CONCLUSIONS

On the basis of the experimental investigations carried out in this research the following conclusions can be drawn:

1. A model relationships between modulus of rupture and both w/c and s/c had been derived and an optimum values for the both values had been indicated in this research as 0.6 and 1.3 respectively.
2. It was noted that variation of w/c has larger effect on flexural strength more than the variation of s/c.
3. In this investigation, a maximum compressive strength of 26MPa at 28 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.
4. The flexural strength of two-stage concrete was found to be similar to that predicted by the ACI equation for flexural strength of conventional concrete. In some cases, the measured flexural strength of two-stage concrete is in fact higher than that predicted by the ACI equation.
5. Since TSC showed a good durability and flexural strength, this will open a good opportunity for more research to implement TSC in highway construction.

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