Behavior of Low to High-Strength Lightweight Concrete under Torsion

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Abstract: Results of an experimental investigation performed to evaluate the effect of various concrete strength levels on behavior of lightweight concrete (LWC) under pure torsion are reported. The principle variable of the testing program was compressive strength of concrete (f'_c) which ranged between 6.9 and 81.4 MPa. Ten mixture proportions were utilized for LWC of 1500 to 2050 kg/m³ unit weight. In total, sixty four (thirty two pairs) rectangular specimens with 100x 200 mm cross-section were tested. Ultimate torsion strength of LWC increases as uniaxial compressive strength increases; however the increase rate reduces for high levels of concrete strengths. The test results are compared with predictions of elastic and plastic theories for torsion and the ACI Code. The Code underestimates the cracking torque of LWC under pure torsion. A regression equation incorporating test results is higher than the ACI equation prediction by a factor of 1.12.

Keywords: high-strength concrete, torsion strength, lightweight aggregate concrete, test.

1. INTRODUCTION

With the rapid development of concrete technology in recent years, higher-strength concrete can be produced much more easily than before. Since 1980. several investigations on mechanical properties of lightweight high-strength concrete have been reported¹⁻⁷. An investigation of the torsional behavior of lightweight concrete (LWC), however, has not received adequate attention. The cracking torsional strengths of LWC with different compressive strength levels determine the maximum torsion can permitted in concrete section not requiring torsional reinforcements according to ACI 318-028.

Torsion can become a predominant action in such structures as eccentrically loaded box beams, curved girders, spandrel beams, and spiral staircases. Prior to 1995, the design and analysis of such members were based on semi-empirical provisions and lacking rationality. Since 1995, ACI-31⁸ has adopted new torsion provisions that seem to be more rational. This new method is based on the thin-wall tube/space truss analogy; however it is not capable of addressing both concrete strength of higher than $f'_c = 69$ MPa and LWC.

The production and use of lightweight aggregate concrete has received considerable attention for structural purposes during the last two decades. LWC with compressive strengths up to 50 MPa can be made readily with high-quality lightweight aggregates. Malhotra¹, and Zhang and Gjorv² have demonstrated that strengths of 70 MPa and higher and a density of less than 2000 kg/m³ are also achievable when silica fume and a superplasticizer are used in the mix. These studies on the material properties of high-strength lightweight concrete (HSLWC) have rapidly advanced material development.

In certain applications, such as bridge decks, bridge girders, and parking garages, the selfweight of structural components represents a large portion of the total load. By reducing the self-weight, considerable savings could be attained, not only in materials but also in construction costs.

Experimental research is required to understand the effect of concrete weight and strength on torsional behavior of LWC. The objective of this research study is to provide information on torsional behavior of lightweight concrete with different levels of strength.

2. EXPERIMENTAL PROGRAM

2.1. Materials and fabrication of test specimens

The effect of concrete strength on torsion behavior of lightweight concrete was investigated through testing of specimens with dimensions of 700x200x100 mm (27.56 X 7.87 X 3.94 in.). The levels of concrete strength represented low to high strength with a range of 6.9 to 81.4 MPa. Ten mix proportions were used for achieving the low, normal and high levels of lightweight concrete strength with unit weights ranging between 1500 to 2050 kg/m . Information regarding torsion specimens and specimens for compressive strength determination are shown in Table 1. In this table the concrete mixture types are identified as: one mix for low strength lightweight concrete (LC), three mixes for normal strength lightweight concrete (NC), and six mixes for highstrength lightweight concrete (HC). The numbers for specimen identification indicate mix design and age of the specimen in days. The experimental program included two specimens for each type of specimen used, and a minimum of three cylindrical specimens were used as control for a desired strength concrete. In total, sixty four (thirty

two pairs) rectangular specimens and ninety six cylindrical specimens were tested.

Cement used was Type I Portland cement conforming to ASTM C150. Coarse lightweight aggregate (slate-based) with a maximum size of 19 mm (0.75 in.) and a specific gravity of 1.54 was used in a saturated surface dry (SSD) condition for HC design mixes (i.e., mixes 5 to 10). Coarse aggregate (LECA) with a maximum size of 25 mm (1.0 in.) and a specific gravity of 1.1 was used in a SSD condition for LC and NC design mixes (i.e., mixes 1 to 4). Fine aggregate had a fineness modulus of 3.12 and a specific gravity of 2.56. Table 2 presents the ten concrete mix proportions used in the testing program.

The following steps were conducted to mix the concrete ingredients:

(1) Coarse and fine aggregate were mixed for one minute in a mixer.

(2) Cement was added to the mix and the materials were mixed for another minute.

(3) The required superplasticizer in mixes 5 to 10 was poured into the total water outside of the mixer, and the solution was added to the mix gradually for a period of three minutes.

(4) The slump test was performed to ASTM C143 standard.

The concrete mixes had slumps of 40 to 110 mm (1.57 to 4.33 in). The specimens were cast with the wide face 700 X 200 (27.55 X 7.87 in) placed horizontally. Also, control cylinders of 152.4 X 304.8 mm (6 X 12 in.) were cast for lightweight concrete. All the specimens were compacted using a table vibrator at a frequency of 5.5 cycle/sec for two minutes immediately after the placement of concrete. All specimens were cured for 24 hours in the mold under a polyethylene sheet

Table 1- Experimental program for torsion and control specimens												
Concrete mixture type Specin		nen	Unit we	Jnit weight, Mix Number of c		ontrol specimens						
	identifica	tion	(kg/n	∩³)	Desi	gn #	for compressive strength			۱		
	LC-1-	7	153	0	1				3			
	LC-1-1	14	153	0	1				3			
Low	LC-1-4	12	152	0	1		3		3			
	LC-1-9	90	151	2	1				3	3		
	NC-2-	7	163	0	2			3				
	NC-2-1	14	163	5	2	2		3				
	NC-2-2	21	162	0	2	2			3	3		
Normal	NC-2-4	42	161	5	2	2			3	3		
	NC-3-	7	158	0	3	}			3	3		
	NC-3-4	42	1550		3	}			3			
	NC-4-2	21	1500		Z	L I			3			
	NC-4-4	42	1505		Z	L I			3	3		
	HC-5-	7	180	0	5	5			3			
	HC-5-	14	1790		5	5			3			
	HC-5-2	21	1795		5	5			3	3		
	HC-5-4	42	1790		5	5			3			
	HC-6-	14	1790		6	6			3			
	HC-6-2	21	1785		6	6			3			
	HC-6-2	28	1790		6	6			3	3		
	HC-7-	3	1900		7	7	3					
High	HC-7-	7	190	5	7	7			3	3		
	HC-7-2	21	190	0	7	7			3	3		
	HC-7-4	42	189	8	7	7			3			
	HC-8-	7	1696		8	3	3		3	3		
	HC-8-	14	1690		8	3	3					
	HC-8-4	42	1690		8	}			3	3		
	HC-9-	7	2051		9		3					
	HC-9-	14	2043		9		3					
	HC-9-2	28	2043		9		3					
	HC-10	-7	2016		10		3					
	HC-10-	28	201	0	10		3					
	HC-10-	42	201	2010		10				3		
Table 0. Oswanata mi		_	1		1		1					
Table 2- Concrete mi	x proportion:	5				0	4:4					
		4		2	4	Quan		7	0	0	10	
Mix design No.		200	2	3	4	2 400	0	7	0	9	10	
Fine aggregate kg/m ³		300) 300	300	320	400	400	200	320	200	505	
Fine aggregate, kg/m ^e		460	500	480	400	300	300	460	280	710	580	
		100	100	100	175	020	030	100	900	370	045	
Superplasticizar/compatiby woight ⁰				100	1/5	100	140	130	142	104	142	
Superplasticizer/cement, by weight%						2.2	Z.Z	Z.Z	Z.Z	Z.Z	2.2	
Water/competitious ratio				10		40	40	40	0.00		00	
			J U.50	0.57	0.51	0.29	0.28	U.25	U.30	U.26	0.23	
	alia Missa 4 4			مانية ٩	Albert 1	E 40	0.01-1	:ta /-!	-			
Coarse aggregate use	un mixes 1-4	s IS Lt	=CA an	a in N	VIIXES	o-10	is Stal	ite (Sla	ate-ba	sea L\	IVA)	
$1 \text{ kg/m}^3 = 0.0624 \text{ lb/ft}^3$												



Fig. 1- Test setup for pure torsion



and then stored in the laboratory environment until expected testing time. Curing time was the basis for obtaining the anticipated concrete strengths. When the anticipated strength was reached, a set of two torsion specimens along with their corresponding control specimens for compressive strength were tested.

2.2. Loading setup and measurements

Details of the test setup are shown in Fig. 1. The general configuration of test set-up is similar to that used by Koutchoukali and Belarbi . One 20 kN hydraulic actuator was used to apply the load near the east support. The load had a 525 mm lever arm from the centroidal axis of the specimen, giving the test rig a 10.5 kN-m torque capacity. A 50 kN tension load cell was used to measure the applied load. The actuator had a stroke length of 152 mm providing a minimum 13 degree twist capacity of the specimen. A reaction arm was used near the west support to balance the applied load by attaching the arm to the laboratory strong floor. The reaction rod had a 525 mm eccentricity from the centroidal axis of the specimen as well. In order to avoid any longitudinal restraint and subsequent compression, the specimen was allowed to slide and elongate freely. This was achieved by supporting the west end of the specimen on rollers.

3. TEST RESULTS AND DISCUSSIONS

Based on test results, the influence of concrete compressive strength on torsional behavior of LWC was determined. The test results of the thirty two pairs of torsion specimens are summarized in Table 3. The compressive strength of specimens ranged

from low to high strength (i.e., 6.9 to 81.4 MPa). The ultimate torsion strength of these specimens, which is almost equal to their cracking strength, is given for average of each pair of specimens tested. The failure occurred at the cracking torsion strength, and afterwards the specimens did not show a softening response. Increase in compressive strength of LWC has improved the ultimate torsion strength; however, the improvement rate decreases with increase in concrete 2). For instance, at strength (Fig. compressive strength of 15.1 MPa, the torsion strength is 958 N.m., whereas at compressive strength of 77.5 MPa, the torsion strength is 2267 N.m (i.e., increase in compressive strength by about four times led to increase in torsion strength by only 140 percent). The maximum torsion strength is 2267 N.m which belongs to the specimen HC-9-28 with compressive strength of 77.5 MPa and unit weight of 2043 kg/m³. Concrete strength of LWC is generally proportional to concrete unit weight; thereby the torsion strength is also proportional to unit weight of LWC.

The cracking torsional moment under pure torsion for normal weight concrete, , is given in ACI 318-02 by the following equation:

$$T_{cr} = 1/3\sqrt{f'_c} \left[\frac{A^2_{cp}}{P_{cp}} \right]$$
(1)

in which the units are MPa and mm. A comparison between the test results for LWC under pure torsion with different concrete strength, and those of ACI (Eq.1) is shown in Fig. 2. It is observed that the ACI equation is conservative for LWC under pure torsion. ACI Code underestimates the cracking torque for LWC under pure torsion. Hence based on the test results, Eq. (1) is modified as follows,

$$T_{cr} = 1/3\alpha \sqrt{f'_c} \left[\frac{A^2_{cp}}{P_{cp}} \right]$$
(2)

In which α is the correction factor for LWC under pure torsion. Based on the experimental results shown in Table 3 and regression analysis, the factor in Eq. (2) equals to . This leads to the conclusion that the ACI Code underestimates the cracking torsional moment for LWC under pure torsion by 12 percent. Similar results were found by Koutchoukali and Belarbi, and Ghoneim and MacGregor based on test results of nine and ninety-four torsional members, respectively, found that the ACI Code underestimates the cracking torque by approximately 32 percent for normal weight concrete. This shows the cracking torque of LWC is up to 20 percent lower than that of normal weight concrete for the same concrete compressive strength.

The proposed cracking torsion strengths using Eq. (2) and percent difference with test results are given in Table 3. The percent difference in torsion strength falls within -7.8 and +11.7 percent, with a summation of the differences equal to -11 percent, which shows the proposed formula is overall conservative. The normal deviation of proposed formula, is defined as the square root of the average of square percent differences as follows,

$$\sigma_m = \sqrt{\frac{\sum (T_{cr,exp} - T_{cr,pro})^2}{n}}$$
(3)

In which $T_{cr,exp}$ is the experimental cracking torsion strength for n = 32 pairs of specimens as shown in Table 3. The normal deviation is 4.8 percent which shows good agreement between test results and the proposed

Table 3- Test results for LC, NC, and HC lightweight concrete specimens									
Specimen	Unit weight	Mix	Concrete	Ultimate Torsion	ACI (Eq.1)	1.12(Eq.1)	Percent		
Identification	kg/m³	Design#	Strength, MPa	Strength, N.m	N.m	N.m	Difference		
LC-1-7	1530	1	6.9	703	582	652	7.2		
LC-1-14	1530	1	7.1	711	590	661	7.0		
LC-1-42	1520	1	8.1	745	634	710	4.7		
LC-1-90	1512	1	8.3	766	642	719	6.2		
NC-2-7	1630	2	12.1	866	772	865	0.1		
NC-2-14	1635	2	15.1	958	864	968	-1.0		
NC-2-21	1620	2	16.5	988	902	1011	-2.2		
NC-2-42	1615	2	18.5	1020	957	1072	-5.1		
NC-3-7	1580	3	11.5	842	753	844	-0.3		
NC-3-42	1550	3	17.6	1011	931	1043	-3.2		
NC-4-21	1500	4	14.6	947	850	952	-0.5		
NC-4-42	1505	4	16.5	977	904	1012	-3.5		
HC-5-7	1800	5	48.1	1635	1540	1725	-5.5		
HC-5-14	1790	5	49.5	1651	1564	1752	-6.1		
HC-5-21	1795	5	55.4	1835	1654	1853	-1.0		
HC-5-42	1790	5	58.5	1769	1700	1904	-7.6		
HC-6-14	1790	6	56.6	1893	1672	1872	1.1		
HC-6-21	1785	6	60.0	1825	1722	1928	-5.6		
HC-6-28	1790	6	65.7	2068	1801	2017	2.5		
HC-7-3	1900	7	27.4	1474	1163	1302	11.7		
HC-7-7	1905	7	42.1	1564	1441	1614	-3.2		
HC-7-21	1900	7	58.0	1900	1692	1895	0.3		
HC-7-42	1898	7	65.8	2066	1802	2018	2.3		
HC-8-7	1696	8	21.0	1246	1018	1140	8.5		
HC-8-14	1690	8	26.3	1269	1139	1276	-0.5		
HC-8-42	1690	8	36.3	1476	1339	1500	-1.6		
HC-9-7	2051	9	52.3	1718	1607	1800	-4.8		
HC-9-14	2043	9	67.6	1898	1827	2046	-7.8		
HC-9-28	2043	9	77.5	2267	1956	2191	3.4		
HC-10-7	2016	10	48.1	1701	1540	1725	-1.4		
HC-10-28	2010	10	73.7	2142	1908	2137	0.2		
HC-10-42	2010	10	81.4	2136	2005	2245	-5.1		



Fig. 2- Comparison of the test results for plain LWC under pure torsion, ACI (Eqs. 1) for normal concrete, elastic and plastic theories predictions.

formula.

3.1. Prediction by elastic theory

St. Venant theory has been extended to the prediction of torsional strength. In applying this theory, the elastic failure torque, , can be written as,

$$T_e = \alpha_e X^2 Y f'_t \tag{4}$$

where α_e is St. Venant's coefficient with value of 0.246 for Y/X=2.0 and f'_t is the tensile strength of concrete which is equal to 0.415 $\sqrt{f'_c}^{12}$. Therefore Eq. (4) reduces to,

$$T_{e} = 0.102 X^{2} Y \sqrt{f_{c}'}$$
 (5)

in which the units are in MPa and mm. Figure 2 shows that the prediction by elastic theory underestimates the results of LWC by approximately 20 percent. Tests on normal weight concrete have shown that this theory underestimates the failure strength of plain concrete by about 50 percent.

3.2 Prediction by plastic theory

Nylander surmised that the extra strength may be contributed by the plastic property of concrete, i.e., concrete may develop plasticity and thus increase the ultimate strength. The plastic failure torque, , can be expressed as follows, assuming full plasticity,

$$T_p = \alpha_p X^2 Y f'_t \quad \alpha_p = (0.5 - X/6Y)$$
 (6)

in which $\alpha_p = 0.416$. This plastic coefficient varies from 1/3 to 1/2, about 50% greater than α_e . Eq. (6) reduces to,

$$T_{p} = 0.173X^{2}Y\sqrt{f_{c}'}$$
(7)

Figure 2 reveals that based on the test results this theory overestimates the ultimate torsion strength of LWC by about 50 percent. The reasons can be (1) concrete has no significant plastic behavior under tension, (2) torsional failure of plain LWC members is quite brittle (i.e., there is no sign of plastic rotation) and (3) the theory cannot account for a size effect.

3.3. Mode of Failure

The observed failure mode of the concrete specimens was very brittle, and increase of concrete strength caused further brittleness and violent failure. These specimens lost their integrity, breaking into two pieces. Figure 3 shows typical failure pattern of LC and HC specimens. At ultimate torque (cracking), a crack at an angle of about 45 developed with respect to longitudinal axis of the test specimen. The LC specimens showed predominantly bond failure at the aggregatematrix interfaces, whereas in NC and HC specimens, the torsional shear cracks passed through 10 to 40 percent of the aggregates along its path.

4. SUMMARY AND CONCLUSIONS

In this paper, strength of plain low- to highstrength lightweight concrete under pure torsion is studied. The concrete compressive strength ranged between 6.9 and 81.4 MPa. Based on the experimental results reported in this study, the following conclusions are drawn.

1. The cracking and ultimate torsion strengths of plain LWC are almost the same. Increase in compressive strength of LWC improved the ultimate torsion strength; however, the improvement rate reduces. In general, the torsion strength is proportional to unit weight of LWC.

2. The ACI equation for torsion strength at cracking is conservative and provides a lower bond for LWC under pure torsion. The regression equation of the test results differs by a factor of 1.12 with that of ACI equation. The proposed regression formula for torsion strength of LWC correlates well with the test results.

3. Prediction by the elastic theory for torsion underestimates the ultimate torsion strength of LWC by about 20 percent; whereas, prediction by plastic theory for torsion considerably overestimates the ultimate torsion strength of LWC.

4. Failure of LWC occurred in a very brittle manner with limited warning before collapse. A major continuous crack at 45° with respect to longitudinal axis caused the failure.

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LIST OF NOTATIONS:

 α = correction factor to adjust ACI formula for LWC under pure torsion α_e = St. Venant's coefficient in elastic theory

 α_p = coefficient in plastic theory A_{cp} = area enclosed by outside perimeter of concrete cross-section

 f'_t = plain concrete compressive strength

 f'_c = tensile strength of concrete

 P_{cp} = perimeter of concrete crosssection

 T_e = elastic failure torque

 $T_{cr,exp}$ = experimental cracking torsional moment of specimen

 $T_{cr,pro}$ = proposed cracking torsional moment of specimen

Tp = plastic failure torque

X = width of the specimens' crosssection

Y = length of the specimens' crosssection

 σ_m = normal deviation defined as the square root of the average of square percent differences.

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