

Torsional behavior of reinforced recycled aggregate flowing concrete hollow section beams

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ABSTRACT

Fifteen reinforced concrete beams made with recycled aggregates and flowing concrete, which were tested under pure torsion to study the torsional behavior. The major parameters in this study were the percent of the recycled aggregates and the number of transverse reinforcements. The torsional response and crack behavior were investigated in this study. From the results, it can be noted that the increase of the recycled aggregate led to a decrease in the critical and ultimate torque of the beam, also, the increasing the number of transverse reinforcements led to the enhancement of the critical and ultimate torque. Numerical analysis by finite element method was conducted and gave a good indicator for agreement in the results of critical and ultimate load between the numerical and experimental study, as well as the angle of twisting of the beam. The second approach was Hsu's softened truss model, the model proves it can predict the critical and ultimate torque for the beam and showed its ability to describe the behavior of the beams before and after cracks.

Keywords: Torsion, Recycled aggregates, Transverse reinforcement, Flowing concrete, Softened truss model

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1. Introduction

The building industry generates a large amount of rubble that may need to be recycled and utilized as recycled aggregates (RAs) to replace natural aggregates in part or whole. Recycling helps to reduce waste and energy consumption, resulting in a more sustainable building sector. Where natural aggregate contains smooth-textured, angular, and elongated particles, recycled aggregate has rough-textured, angular, and elongated particles.

The compressive strength, flexural strength, and stiffness of hardened concrete formed using recycled aggregate are slightly lower than those of concrete made with conventional aggregates [1-8]. Flowing concrete was employed due to the lack of workability caused by the use of recycled aggregates. In recent decades, the use of flowing concrete has increased dramatically. The concrete must have an adequate level of passing ability, filling ability, and stability in order to fill the entire space and flow through the formwork without any external effort [9, 10]. Flowing concrete is defined by ACI committee 116 [11] as concrete with a slump larger than 7.5 in. (190mm) while remaining cohesive. Concrete that flows or has a good workability Concrete with low cement content and high cement replacement materials like fly ash (FA) and ground granulated blast-furnace slag (GGBS) would be a cost-effective solution to make long-lasting concrete. [10] [Nan Su]. However, flowing concrete is susceptible to segregation, and strong flow combined with high form pressure and low form leakage increases sensitivity to plastic shrinkage and early cracking [Peterson] [12]. The structural behavior of beams cast using self-compacting concrete including recycled concrete aggregate as coarse aggregate at various replacement ratios is investigated in this study. This research includes an

experimental component that entails the casting and testing of fifteen beams. The percentage of recycled aggregate and the elongation reinforcement ratio are the two most important variables. The study's second goal was to see if Hsu's softened truss model [13] was valid in the scenario of recycled aggregate being reincorporated into the concrete mix. In addition, this research developed the "Softened Membrane Model for Torsion (SMMT)" theory[14] to predict the torque-twist curve, including the pre-cracking, post-cracking, and post-cracking responses for a concrete beam under torsion with flowing concrete containing recycled concrete as coarse aggregate, by adding a factor that causes the tensile strength and strain gradient of the c to change. Finally, using the ANSYS program 18.2, experimental beams were finite element evaluated.

2. Test program

The experimental program included the testing of fifteen beams under pure torsion. Table 1 shows the details of the beams that were tested. All of the beams have the same 300x300mm² cross-section and are 1300 mm long. The longitudinal reinforcement was the same for all beams, Ø12mm at each corner. The transverse reinforcement and the percentage of recycled aggregates replacement were the primary variable. Fig. 1 shows the details of tested beams.

Table 1. Details of the experimental specimens

Group	Beam number	Number of transverse reinforcement	Recycled aggregates percentage (%)
A	T0R0	without	0
	T6R0	Ø10@60mm	0
	T12R0	Ø10@120mm	0
B	T0R20	without	20
	T6R20	Ø10@60mm	20
	T12R20	Ø10@120mm	20
C	T0R40	without	40
	T6R40	Ø10@60mm	40
	T12R40	Ø10@120mm	40
D	T0R60	without	60
	T6R60	Ø10@60mm	60
	T12R60	Ø10@120mm	60
E	T0R80	without	80
	T6R80	Ø10@60mm	80
	T12R80	Ø10@120mm	80

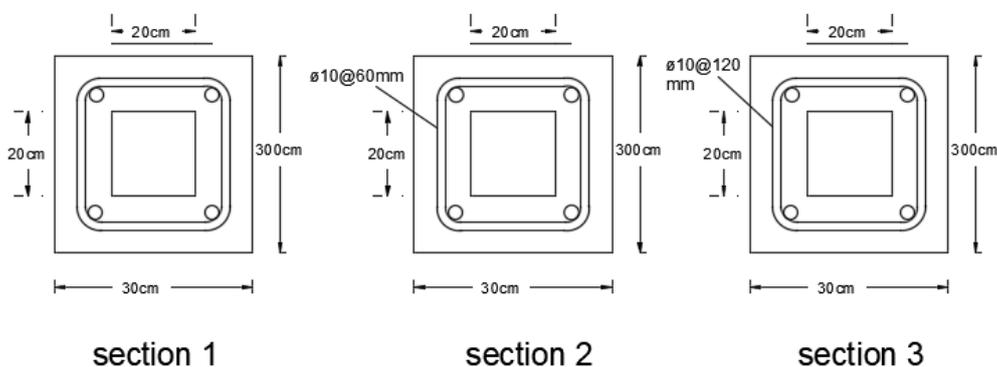


Figure 1. Details of experimental specimens

The first number of beam distinguishes being the amount of steel reinforcement and the second number representing the proportion of recycled aggregates. The reinforcing steel's average yield strength and modulus of elasticity were 420 N/mm² and 1.98x10⁵ N/mm² correspondingly.

The recycled aggregates used in this investigation came from the demolition of concrete cubes that had been delivered to the lab for testing (see Fig. 2) Its grading complied with B.S. 882-1983 [23], and the aggregates' maximum size was 20 mm. To obtain the specified level of workability, the same amount of additive was employed in all mixes. It was made of cement, sand, and other materials. At 28 days, the average cubic compressive strength was above 32 N/mm², with water-cement ratios of 1.0, 1.1, 2.1, and 0.42, respectively. Two types of concrete mixes were created: one with natural gravel as coarse aggregate and the other with recycled concrete aggregate with varying coarse aggregate replacement ratios. Table 2 shows the computed characteristics of concrete mixtures.



Figure 2. Recycled aggregates

Table 2. Concrete mixture proportions and properties

Ingredient	Unit	Recycled aggregate replacement %				
		0	20	40	60	80
Cement Type I	Kg/m ³	350	350	350	350	350
Fine Aggregate	Kg/m ³	755	755	755	755	755
Water	Kg/m ³	168	168	168	168	168
Coarse Aggregate	Kg/m ³	1000	810	520	220	188
Recycled aggregate*	Kg/m ³	0	185	375	570	710
Superplasticizer	Kg/m ³	2.100	2.610	2.820	3.120	3.312
properties						
Slump	mm	245	240	237	235	230
Compressive strength	MPa	33.3	30.6	28.9	26.5	24.6
Splitting tensile strength	MPa	2.81	2.47	2.10	1.75	1.67

The Universal Testing Machine Model (855 IMFI System) was used to test all of the beams, which has a maximum load capability of 300 tons. The beams had a clear span of 1.3 meters, and the specimens were placed in a test machine with roller support at each end. To measure torsional rotations, a set of linear variable differential transformers (LVDTs) was installed under four arms that were projected normal to the beam axis. Three electrical resistance strain gages, each 10 mm long, were mounted at a 50 mm interval on one of the longitudinal bars' corners to record longitudinal strain.

Three electrical resistance strain gauges were installed on the beam surface in the middle with a 45-degree angle to the beam axis to measure the diagonal concrete strain. A hand-held microscope with an accuracy of 0.001 mm was used to record the data and measure their widths. Fig. 3 depicts the test setup.



Figure 3. Test setup for beams

3. Experimental results

3.1. Torsional strength and behavior curves

Table 3 shows the experimental results of the tested beams.

Table 3. Summary of test results

Group	Beam Number	T_{cr} kN.m	T_u kN.m	$\frac{T_u}{T_u cont.}$	Θ_{cr}	Θ_u	$\frac{\theta_u}{\theta_u cont.}$
A	T0R0	90	100	--	0.85	1.09	---
	T6R0	82	111	1.11	1.11	2.14	1.96
	T12R0	115	130	1.30	1.20	3.11	2.85
B	T0R20	81	90	--	0.84	1.65	---
	T6R20	68	94	1.04	0.71	1.74	1.05
	T12R20	111	125	1.38	0.51	2.24	1.36
C	T0R40	74	82	---	0.82	1.04	---
	T6R40	66	88	1.07	0.57	0.85	0.81
	T12R40	121	125	1.52	0.43	1.84	1.77
D	T0R60	70	75	---	0.48	0.85	---
	T6R60	61	80	1.07	0.39	0.74	0.87
	T12R60	101	102	1.36	0.41	1.21	1.42
E	T0R80	54	70	---	0.33	0.54	---
	B6R80	62	77	1.10	0.24	0.74	1.37
	B12R80	108	90	1.28	0.15	1.13	2.09

Table 3 shows that the beams with 100 percent recycled aggregates, group E, with various percents of transverse reinforcement (0, 10 @ 60, and 120 mm) showed increases in critical and ultimate cracks as the percent of transverse reinforcement increased; this had the same effect for all the groups (A, B, C, and D), but with lesser percent increases.

The effect of recycled aggregate may be seen in beams TOR0, TOR20, TOR40, TOR60, and TOR80 that do not have a transverse reinforcement and contain recycled aggregates of 0, 20, 40, 60, and 80 percent. It can be shown that the critical and ultimate torques decrease as the recycled aggregate content increases, which is also true for other beams with transverse reinforcement of 10 @60 and 120mm, as shown in Figure 4. The curve for specimens without transverse stirrup was more regressive than the other curves, indicating that the influence of recycled aggregate increased with beams without transverse reinforcement.

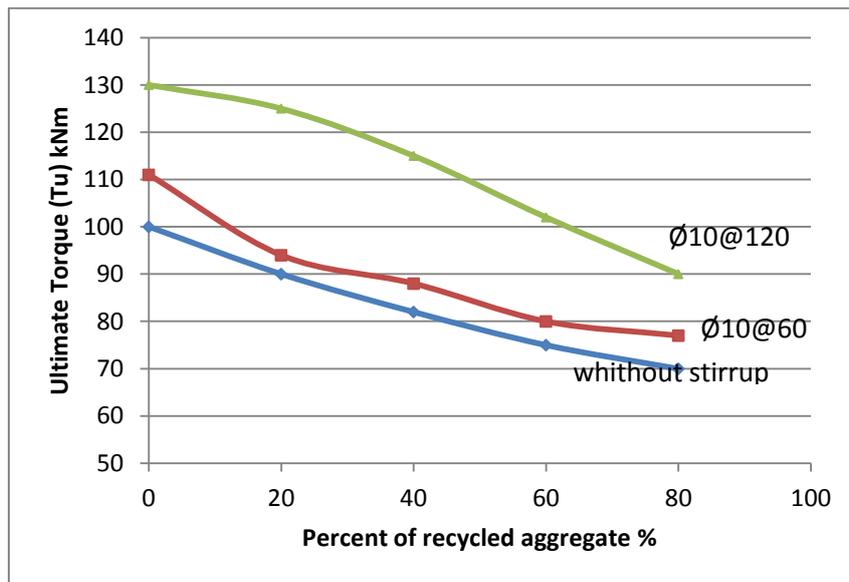


Figure 4. Graph of test results

Fig. 5 depicts the correlations between ultimate torque and twist for a typical tested beam. The curves are linear in general, with stiffness approximately equal to all beams, but they become nonlinear after a crucial torsional load. It should also be noted that the transverse reinforcement improves the beam's ductility, but the usage of recycled aggregates reduces the beam's ductility

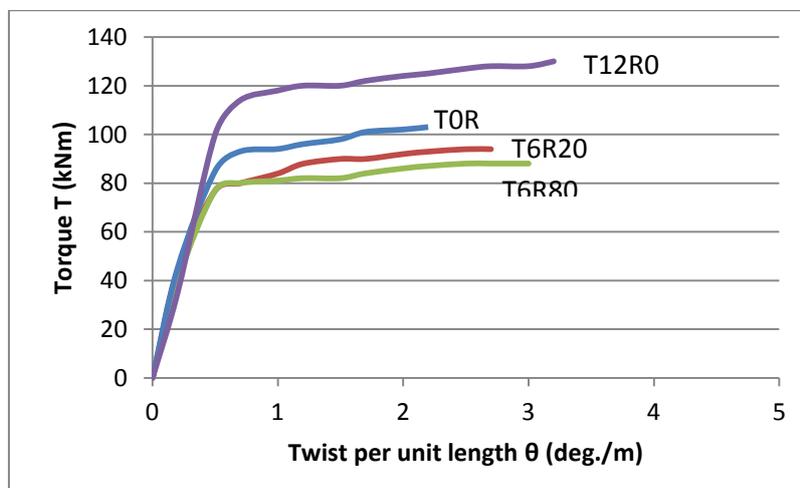


Figure 5. Experimental torque-twist response for beams with normal aggregate

4. Finite element analysis

The model of the tested beams was represented in this study using the ANSYS 18.2 tool. Concrete and reinforcement steel were represented using the 8-node SOLID65 brick element and the 2-node LINK180 discrete element, respectively. The qualities of the materials were the same as those used in the experimental program. Fig. 6 explains the finite element model and the approach to the applied load, as well as the boundary conditions. Loads were applied at the ends of the beam in opposing directions as torsional loads.

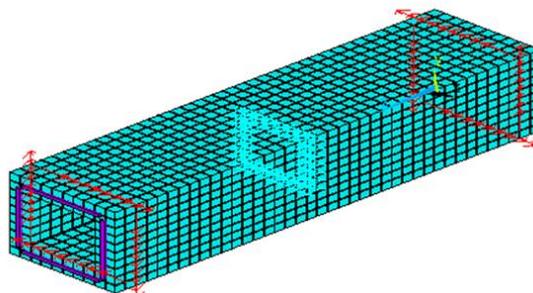


Figure 6. Model of the tested beams

Table 4 shows a comparison of theoretical and experimental results, with the theoretical showing good agreement.

Table 4. Comparison results between theoretical and experimental results

Beam	Ultimate torque (kNm)			$\frac{T_{test}}{T_{FE}}$	$\frac{T_{test}}{T_{cal.}}$	Ultimate twist(deg./m)			$\frac{\theta_{u,test}}{\theta_{u,FE}}$	$\frac{\theta_{u,test}}{\theta_{u,cal.}}$
	Tu,exp.	Tu,FE	Tu,cal.			$\theta_{u,exp.}$	$\theta_{u,FE}$	$\theta_{u,cal.}$		
T0R0	100	108	105	0.93	0.95	1.09	1.20	1.1	0.90	0.99
T6R20	94	100	104	0.94	0.90	1.74	1.85	1.64	0.94	1.85
T6R80	77	81	72	0.95	1.07	0.74	0.68	0.81	1.09	0.91
T12R0	130	137	124	0.94	1.05	3.11	3.23	3.44	0.96	0.90

5. Mode of failure

Fig. 7 depicts the typical failure of the tested beams. Almost all models fail in the expected manner. Spiral diagonal fissures emerged around the 45-degree cross-section, and the concrete crumbled as the load increased. For beams with recycled aggregates, the cracks emerged at varied angles.



Figure 7. Cracks pattern of all tested beams

The ultimate and twist angles for tested beams have been determined to evaluate the validity of Hsu's softened truss model. Table 5 summarizes the findings of the tested and theoretically derived beams. The projected ultimate torque and angle of twisting at ultimate load were found to be in good agreement. Fig. 8 illustrates the experimental torque twist for the T6R80 beam, as well as two ANSYS and Hsu's softened truss model-predicted curves. The truss model's capacity to predict the torque twist curve's initial stage before crack and post crack stages can be seen. Furthermore, the finite element method demonstrated its capacity to predict the stages preceding and following cracks.

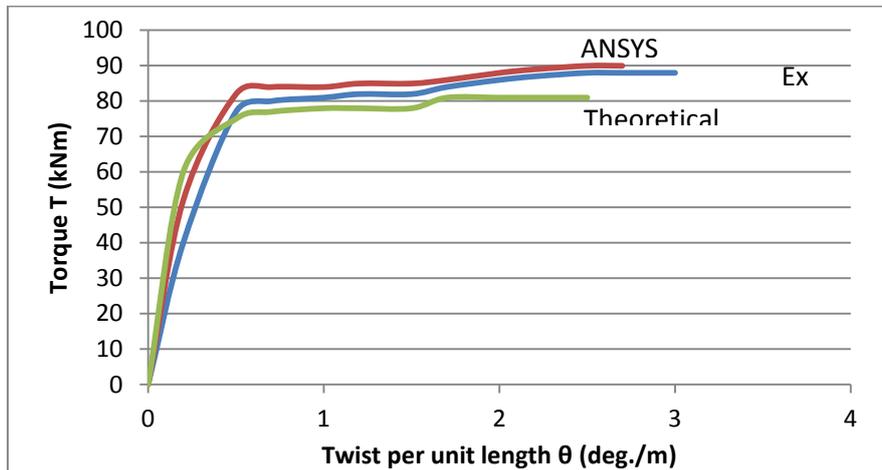


Figure 8. Comparison between experimental, ANSYS and theoretical curves (T6R80)

6. Conclusion

The experimental program includes the testing of fifteen beams under pure tension to investigate the behavior of reinforced concrete with recycled aggregates for flowing concrete and various transverse reinforcing options. The results show that as the percentage of recycled aggregates in the concrete mix is increased, the critical and ultimate torque decreases. The cracking and torsional strength of beams with normal aggregates and maximum transverse steel reinforcement will be the highest.

The analytical prediction of the ultimate and angle of twisting by finite element and by Hsu's softened truss model is the second part of the investigation, and it was discovered that the results by finite element and experimental corresponding to it are in good agreement. The capacity of Hsu's softened truss model to forecast the ultimate torque and angle of twisting of the beam, as well as show the behavior of the beam at the first and second stages after cracking the beam, was also discovered.

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