EXPERIMENTAL STUDY ON PUNCHING SHEAR OF LIGHTWEIGHT CONCRETE SLAB

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ABSTRACT

The punching shear failure is a critical design aspect for 2-way slabs, since punching shear is usually the governing failure mode for flat slabs and it could lead to brittle failure of the slab-to-column or column-to-foundation connections. Several equations to predict the punching shear strength of the slab are available. Since these equations are derived from the statistical fit of test results available at the time of developing these equations, they are empirical formula in nature and the prediction values calculated from them fluctuate widely. Also, few previous studies on the punching shear behaviour of lightweight concrete slabs exist. This paper presents the punching shear behaviour of lightweight concrete slabs through a series of experimental studies. Punching shear tests were conducted for slabs with two different types of lightweight aggregates and their punching shear behaviors were compared with that of normal-weight concrete slab. The results indicated that the surface angle of punching shear failure is significantly affected by the types of lightweight aggregates used. Finally, test results were compared with present design specifications in order to examine the validity of the code equations currently used to predict the punching shear strength of lightweight concrete slabs.

Keywords: Punching shear, Lightweight concrete, Concrete slab.

1. INTRODUCTION

Lightweight aggregate has a relatively lower specific density than normal aggregate (Expanded Shale Clay and Slate Institute 1971). Different definitions of lightweight aggregate are available in international design codes and standards for concrete structures (ACI 2011; BS EN 206-1 2000). For example, an aggregate with dry loose bulk density smaller than 1,200 kg/m^3 can be considered as a lightweight aggregate in Korea (Korean Agency for Technology and Standards 2002). While

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the use of lightweight aggregate concrete (LWAC) is not common due to its high cost, its high strength/weight ratio makes it a versatile construction material. Thus, higher cost may often be offset by the reduction in dead-weight loading (Dhir et al. 1984), especially for the slabs of high-rise building.

The punching shear failure is a major design concern in concrete flat slab designs. Many design models to predict the punching shear resistance capacity of the slabs are available (ACI 2011; CEB-FIP 1990; CSA 2004; EC2 2004), however the predictions vary according to the type of model used since the prediction models are based on the statistical fit of test results available at the time of developing the models (Choi et al. 2007; Elshafey et al. 2011). Furthermore, only a few studies on the punching shear resistance capacity of LWAC slab are available (Cho et al. 2006; Marzouk et al. 2000; McLean et al. 1990; Pantelides et al. 2012; Theodorakopoulos and Swamy 2002).

In this study, the punching shear resisting capacity of LWAC slab was investigated through a series of experimental studies. Two LWAC slabs and one normal concrete slab were constructed and tested in order to evaluate the load-displacement capacities and the surface angle of punching shear failure. Two different types of lightweight aggregates (a shale coarse aggregate with crushed shapes, and a clay coarse aggregate with spherical shape) were used. Also, the experimental results of this study were compared with the estimated shear capacity from design code models to examine the effectiveness of current design codes.

2. EXPERIMETAL STUDY

2.1. Materials

In this study, two different types of artificially produced coarse lightweight aggregates were used as shown in Fig. 1.

(a) (b)

Figure 1: Lightweight coarse aggregates used in this study: (a) Type A; and (b) Type D.

One is a shale coarse aggregate with crushed shapes, named as “Type A” and the other is a clay coarse aggregate with spherical shapes, named as “Type D”. The properties of each lightweight aggregate are provided in Table 1.

Table 1: Physical properties of lightweight coarse aggregates

	Type A	Type D
Raw material	Shale	Clay
Maximum size (mm)	19	12
Dry loose bulk density (kg/m^3)	800	700
Specific gravity	1.63	1.40
Shape type	Crushed	Spherical
Water absorption (%)	12.0	24.0

Table 2: Concrete mixture proportions

Mixture	Cement	Fly-ash	Water	Aggregate			Remark
				Fine	Coarse	LWA	
NN	351	39	152	807	968	-	Normal weight
LA	351	39	152	807	-	521	Type A
LD	351	39	152	807	-	607	Type D

Type I Ordinary Portland Cement and fly-ash (Class C) from coal-burning power plant were used for all concrete mix designs. All mixtures tested in this study had the same water-to-binder (w/b) ratio of 0.396. 10% of the cement weight was replaced by fly-ash for all mixtures. Table 2 presents the mixture proportions used in this study. NN in Table 2 represents normal concrete mixture with normal coarse aggregate, while LA and LD are lightweight aggregates concrete (LWAC) mixtures with Type A and Type D lightweight aggregates, respectively. The normal concrete mixture (NN mixture) in Table 2 is widely adopted for slab construction in Korea. Normal-weight sand was used for LA and LD mixture in order to meet the standard of sand-lightweight concrete specified in ACI (2011). The mix design should have the following required conditions; a slump of 190-220 mm and a minimum 28-day cylindrical compressive strength of 30 MPa for the high-rise building slab construction. The cylindrical compressive strength f_c', the splitting tensile strength f_{sp}, the modulus of elasticity E_c, and the unit density were measured. The measured mechanical properties are summarized in Table 3.

Table 3: Average mechanical properties of normal and lightweight concrete

Mixture	Compressive strength f_c' (MPa)	Splitting tensile strength f_{sp} (MPa)	Modulus of Elasticity E_c (GPa)	Unit density (kg/m^3)
NN	40.6	3.41	31.7	2,335
LA	37.2	3.40	22.6	1,898
LD	34.2	2.82	20.0	1,847

2.2. Test setup

Two LWAC slabs and one normal-weight concrete slab were constructed. NN slab was manufactured with normal concrete mixture (NN mixture) as a reference slab, while LA and LD slabs were lightweight concrete slabs made of LA and LD concrete described in the previous section, respectively. All three slabs had the same dimensions and reinforcement layout. Figure 2 shows the test setup and the dimensions of the slabs. The layout of reinforcement is also shown in Fig. 2. The bottom flexural reinforcing bar consisted of D10 bars spaced at 150 mm, where the yield stress and the diameter of D10 bar are 411 MPa and 9.53 mm, respectively. In the case of the top flexural reinforcing bar, D10 bars were spaced at 300 mm except the region near the edge of the slab, where the spacing of the bars within 500 mm from the slab edge was 150 mm as shown in Fig. 2. The cover depth is 20 mm for the top and the bottom reinforcement. Shear reinforcing bars were not installed for all specimens. The slabs were placed at the same time and cured under the same conditions. The vertical displacement was applied through 300 mm square steel plates, where the thickness of the plate was 35 mm and the loading rate was 0.005mm/sec. The vertical displacement of the slab was measured by the linear variable differential transducers (LVDTs) installed below the bottom of the test specimen. The locations of LVDTs are also shown in Fig. 2.

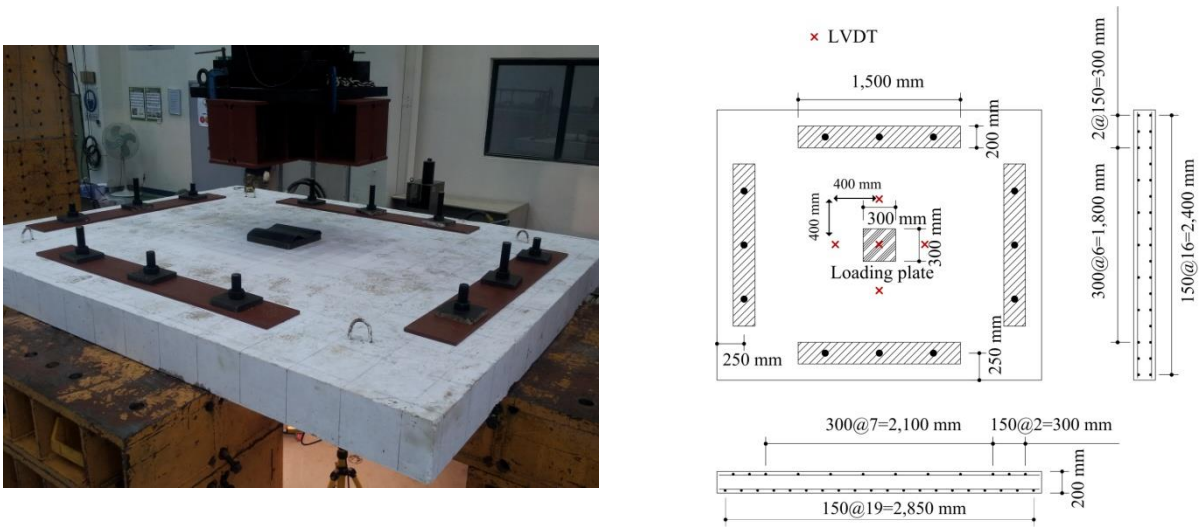

Figure 2: Test setup and dimensions of specimen.

2.3. Test results

Figure 3 shows the relationship between the applied load and the vertical displacement of the test specimen at the loading point. All slabs failed by punching shear. The applied load vs. vertical displacement curves of three test specimens were similar to each other up to the punching shear failure point even if the E_c of LA and LD slab was considerably lower than the NN slab. Then, the applied load was suddenly dropped at the point of punching shear failure. From the test results, the punching shear resisting capacity, P_{ut}, was determined as 670.4 kN, 552.0 kN and 626.3 kN for NN, LA and LD slab, respectively, as shown in Fig. 3.

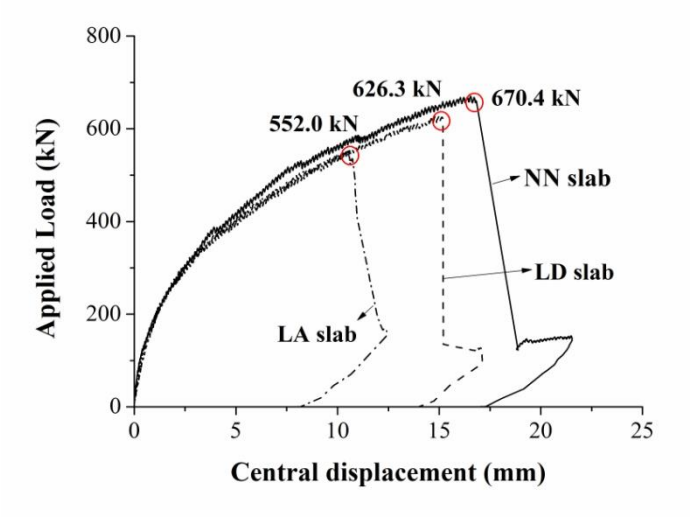

Figure 3 Applied load vs. vertical displacement of the test specimens.

Figure 4 Punching shear failure surface: (a) LA Specimen; and (b) LD specimen.

All slabs were cut after the test to observe the damage pattern of punching shear failure surface. Figures 4(a) and (b) shows the failure surface of LA and LD slabs, respectively. The average angle of the failure surface, which was measured from the top surface, of NN, LA, and LD slabs was 30.4°, 27.8°, and 20.5°, respectively. The angles of failure surface for NN and LA slabs were similar to each other, while the surface angle of punching shear failure for NN and LD slabs was considerably different from each other. The average surface angle of punching shear failure for LD slab was approximately 48% lower than that of NN slab.

3. COMPARISON WITH CURRENT DESIGN CODES

Test results were compared with punching shear resistance capacity obtained from current design codes (ACI 2011, CEB-FP 1990) as summarized in Table 4. From Table 4, the CEB-FIP model (1990) underestimated the punching shear resisting capacity by an average of 28% for all three test specimens, while the ACI design model (2011) overestimated punching shear resisting capacity of LA slab by 20%. The ACI code underestimated the punching shear resistance capacity of LD slab by 10% as shown in Table 4.

In ACI (2011), the reduction factor λ is taken as 0.85 for sand-lightweight concrete, and if the average splitting tensile strength, f_{sp}, of lightweight concrete is specified, λ can be obtained as

$$\lambda = f_{sp} / \left(0.56\sqrt{f_c'}\right) \leq 1 \quad \text{(in MPa unit).} \tag{1}$$

In this study, Eq. (1) was used to evaluate λ because f_{sp} is measured. The f_{sp} of LA slab is almost identical to NN slab, as shown in Table 3. The λ of LA slab was calculated as 0.995 from Eq. (1), and is almost equal to the one that is used for normal concrete. As a result, the calculated punching shear resistance capacities of LA and NN slabs based on the ACI code model were similar to each other. However, the punching shear resistance capacity of the LA slab was 21% lower than the NN slab from the test results. Thus, the ACI model (2011) gave an unconservative prediction of the punching shear resistance capacity of the LA slab. When a λ of 0.85 was used for the LA slab, the discrepancy between the test results and the predicted punching shear resistance capacity was reduced up to 7%. The crushed shape of coarse aggregate in LA specimen may result in an increase of f_{sp}. However, this didn't guarantee the enhancement of the punching shear resistance capacity of the LA slab. Thus, care should be taken to use Eq. (1) even when f_{sp} is available. In the case of LD slab, the λ from Eq. (1) was 0.86, and it was very close to the 0.85 used for sand-lightweight concrete.

Table 4: Comparison of test results with current design codes

Specimen	Experimental results (kN)	ACI (kN)		CEB-FIP (kN)	Test/ACI	Test/CEB-FIP
		λ = 0.85	λ from Eq. (1)			
NN slab	670.4	726.6	726.6	492.2	0.92	1.36
LA slab	552.0	591.3	692.4	478.1	0.80	1.15
LD slab	626.3	566.9	574.3	464.8	1.10	1.34

Furthermore, it can be seen that punching shear resisting capacity of LD is considerably higher than LA specimen even if f_{sp} of LD is 17% lower than that of LA specimen. The critical perimeter is a major parameter affecting the punching shear resistance capacity of the slab. Since the surface angle of punching shear failure for the LD slab was considerably less than that of the NN and LA slabs. it may have caused the increase in the critical perimeter of the LD specimen.

4. CONCLUSIONS

In this study, the punching shear resistance capacity of lightweight aggregate concrete (LWAC) slabs was investigated through a series of experimental studies. Based on the experimental results, the following conclusions were made:

1. It was found that the surface angle of punching shear failure for LWAC slabs with spherical-shape coarse aggregate (LD slab) was less inclined than that with crushed-shape coarse aggregate LA slabs. This resulted in an increase of the critical perimeter of the LD slab. On the other hand, the failure surface angle of LA and NN slabs was similar to each other.

2. The λ of LA slab was 0.995 from Eq. (1), since f_{sp} of LA slab is almost identical to the NN slab. The crushed shape of coarse aggregate in the LA specimen may result in an increase of f_{sp}. However, the punching shear resistance capacity of the LA slab was approximately 21% lower than that of the NN slab. The increase of f_{sp} didn't guarantee an enhancement of shear strength for the LA slab. Thus, care should be taken to use Eq. (1) even when f_{sp} is available.

5. ACKNOWLEDGMENTS

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