SIZE EFFECT ON PUNCHING SHEAR BEHAVIOR OF SLAB-COLUMN ASSEMBLY MADE FROM ENGINEERING CEMENTITIOUS COMPOSITE MATERIALS WITH POLYVINYL ALCOHOL FIBERS

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ABSTRACT: Engineering Cementitious Composite (ECC) materials with PolyVinyl Alcohol (PVA) fibers are employed to investigate the effect of the ductile matrix on the behavior of flat plate-column connection. Totally four slabs are cast and tested, three of PVA-ECC slabs are compared to control slab of normal concrete. The thickness of the slabs used was variable (50, 60 and 80 mm) in order to investigate the effect of the size, and keeping the other size is constant (500 × 500 mm). All four slabs are reinforced with same conventional reinforcement ratio. The results showed that in the ductility of the slabs made from PVA-ECC are significantly enhanced compared with the normal concrete slab, this ductility improvement decrease with increasing the slab thickness, and more over the shear stress in the specific location is reducing with increasing the slab thickness.

INTRODUCTION

Flat plate-column assembly is one of most important connection members in structural system, especially when the height of the story is preferable. This connection is however governed by brittle punching shear failure. Many attempts and had been conducted to decrease the effect of the brittleness of the punching shear behavior, such as, using special shear reinforcement. Recently, the researchers seek to increases the ductility with keeping the same amount of the flexural reinforcements. However, the effect of slab thickness is still of the matrix aggravated the brittleness problem. Many researchers had been observed that increasing in the thickness of the slabs will rapidly decrease the shear stress resistance (Bazant & Cao, Brickle & Dilger and Mutton & Schwartz) however, not all codes of practice are considered the size effect, such as ACI318 (ACI318-14). Some codes are considered this effect but with deferent forms. Eurocode 2 (EN1992-1-1) and DIN1045 (DIN1045-2) represent the size effect (ξ) as ξ = 1+ 200/d. Brickle and Dilger (Brickle & Dilger) observed that when using ACI318's equation, only 89 % of nominal shear resistance was reached for the slab of 300mm thickness, this percentage decrease to be 64 % for the slab of 500 mm (Guandalini et al).

Many researchers had been proposed different factor to capture the size effect on the punching shear strength. Broms (Broms) proposed his size effect factor based on assumption that the initiation of the cracks at the compression zone in the early hydration stage has an important role, his factor is produced in term of compression depth (xpu) as ξ = (0.15/xpu)1/3, which in turns proportional with rebar ratio, the cubic root in term of effective depth (ξ = (500/d)1/3) is proposed by Shehata (Shehata). Regan (Regan) shows that the fourth root is best introducing the size factor in term of effective depth ξ = (1/d)1/4.
In the current work, slabs of different thickness made from PVA-ECC are cast and tested in order to investigate the effect of the size, on the punching shear strength. Authors of the current work demonstrate that the effect of size importantly needs further researches.

EXPERIMENTAL PROGRAM

Slab Geometry and Materials

The experimental program included casting and tested four flat plates of square shape that most convenient to fabricate, the length of the sides are 500 × 500 mm. Three slabs coded as (V5, V6, and V8) of PVA-ECC matrix reinforced by steel reinforcement bars in addition to 2 % by volume PVA fibers, the properties of the physical of PVA fibers are summarized in Table 1. The three slabs are compared to control slab of normal reinforced concrete. The main parameter is the effect of slab thickness (h), where the three slabs thicknesses were 50, 60, and 80 mm, and the control specimen is of 50 mm thickness. The column stub size (c) is constant for all slab thickness that is of 55× 55 mm steel plate.

The flat plates are designed as its corresponding conventional reinforced concrete slab, which fail due to punching shear effect; therefore all tested slabs were reinforced by one layer of convenient flexural reinforcement by ϕ5.3 mm deformed bars, with 400 MPa yield strength. The ends of reinforcement bars are bent by 90 deg, one additional bar in each direction of the free ends are added. The concrete cover was 15 mm at all slabs. The reinforcement ratio (ρ = 1.2 %) was constant for all slabs, so there are different spacing bars, Figure 1. shows the slabs reinforcements details.

Table 1. Physical Properties of Polyvinyl Alcohol (PVA)

Density	l_f	D_f	l_f/D_f	Tensile strength	Elastic modulus
kg/m³	mm	mm	mm/mm	MPa	GPa
1260	6	0.015	400	1600	34

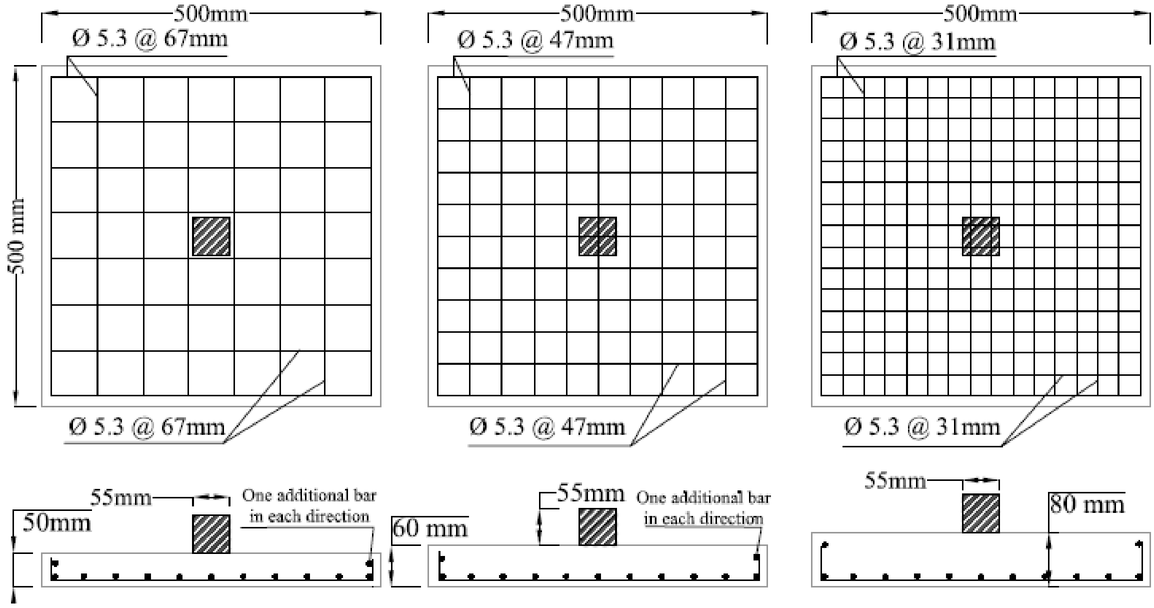


Figure1. Slab Geometry and Reinforcement Bars Details.

All slabs with PVA-ECC are cast in one batch, and the normal reinforced concrete slab is cast in a different batch. The materials used for the PVA-ECC slabs are summarized in Table 2. Portland cement of type CEM II/ A-LL 42.5 R for both ECC and normal concrete are used. The dense concrete is planned to use in the production of the normal concrete. The same mix proportion of Bazant and Cao (Bazant & Cao) recent work which is given in Table 2 are used for normal concrete where the fine aggregate content represents 63% of the total aggregate with 9.5 mm maximum size of aggregate, while the PVA-ECC does not include coarse aggregates. Therefore it can be regarded as fiber reinforced mortar. Dense nature of the two mixes is favourable to increase both concrete strengths (tensile and compressive), and increasing the interactions between the matrix and the fibers, and also to maximize the ductility by developing micro cracks.

The designed 28-days compressive strength (f 'c) of the standard cylinders (100 × 200 mm size) for the two mixes were 45 MPa, the actual compressive strength of the normal concrete and the PVA-ECC were 43.2 and 38.6 MPa, respectively. For the normal concrete mix, the dry materials are mixed for 10 minutes and then the water added with increasing the vertical mixer speed. For ECC, the dry binder materials (cement + fly ash) and the silica sand are mixed for three minutes at slow speed, after which the specified water is added with increasing the mixer speed to 30 minutes, in this stage the Superplasticizer is added for 2 minutes and then the PVA fibers are interspersed by hand during the mixing. After mixing is complete the matrix is molded and externally consolidated for ECC, internally vibrated for normal concrete slabs, and rodded for standard cylinders. In order to overcome the errors, three standard cylinders were cast for each standard test, where the compressive and tensile strength are evaluated in this work. The slabs and the standard cylinders were kept for 24 hours in laboratory condition, and then cast specimens are mold and cured for 28 days in the water tank.

Table 2. Mix for the PVA-ECC and Normal Concrete

mix. code	Fiber	Water	Cement	Fly ash	Silica Fume	Sand	Crashing stone	Silica sand	Super plasticizer
	%	lt	Kg/m^3	Kg/m^3	Kg/m^3	Kg/m^3	Kg/m^3	Kg/m^3	Kg/m^3
P	0	216	465	-	35	1170	680	-	6.6
V	2	352	551.4	662	-	-	-	441.12	7.33

Test Setup and Instrumentation

The test setup is followed the authors' recently work (Abo Altemen et al), where the slabs are supported on eight steel half balls, in order to represent the line of the contra flexure, the balls symmetrically distributed in a cycle of 400 mm diameter, the central angles were π / 4 as shown in Figure 2. The yield line analysis is based on Equation 1, that produced by (Guandalini et al.)

$$P_{flex} = \frac{4\, m_R}{r_q\left(\cos\left(\pi/8\right) + \sin\left(\pi/8\right)\right) - c} \times \frac{b^2 - (b \times c) - (c^2/4)}{b - c} \qquad \text{Equation 1}$$

Where, b, c, π, and r_q are depicted in Figure 2, the section moment capacity m_R are obtained as follows (Guandalini et al).

$$m_R = f_y \times \rho \times d^2 \times \left(1 - 0.5\rho \times \frac{f_y}{f'_c}\right) \qquad \text{Equation 2}$$

where d is the average effective depth of the section equal to $(d_1 + d_2)/2$, f'_c and f_y are the concrete compressive strength and bars' yield strength, respectively, and ρ is the reinforcement ratio taken as a sort of averaging as follows,

$$\rho = \frac{\rho_1 d_1^2 + \rho_2 d_2^2}{2d^2} \qquad \text{Equation 3}$$

In addition to the jack displacement of a test machine, the deflection at the centre of the slab is measured using Linear Variable Differential Transformers (LVDT) located at the centre of the bottom face. The monotonic increasing load is applied through steel plate located at the centre of the slab; the load was applied in displacement control rate of 0.4 mm/min.

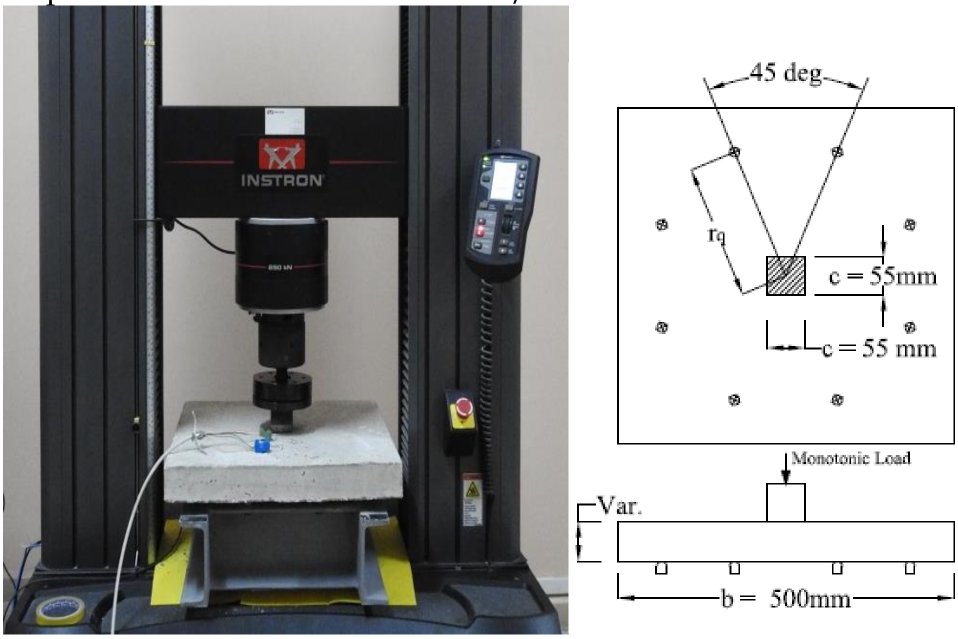


Figure 2. Test Setup and Supporting Details

EXPERIMENTAL RESULTS AND DISCUSSION

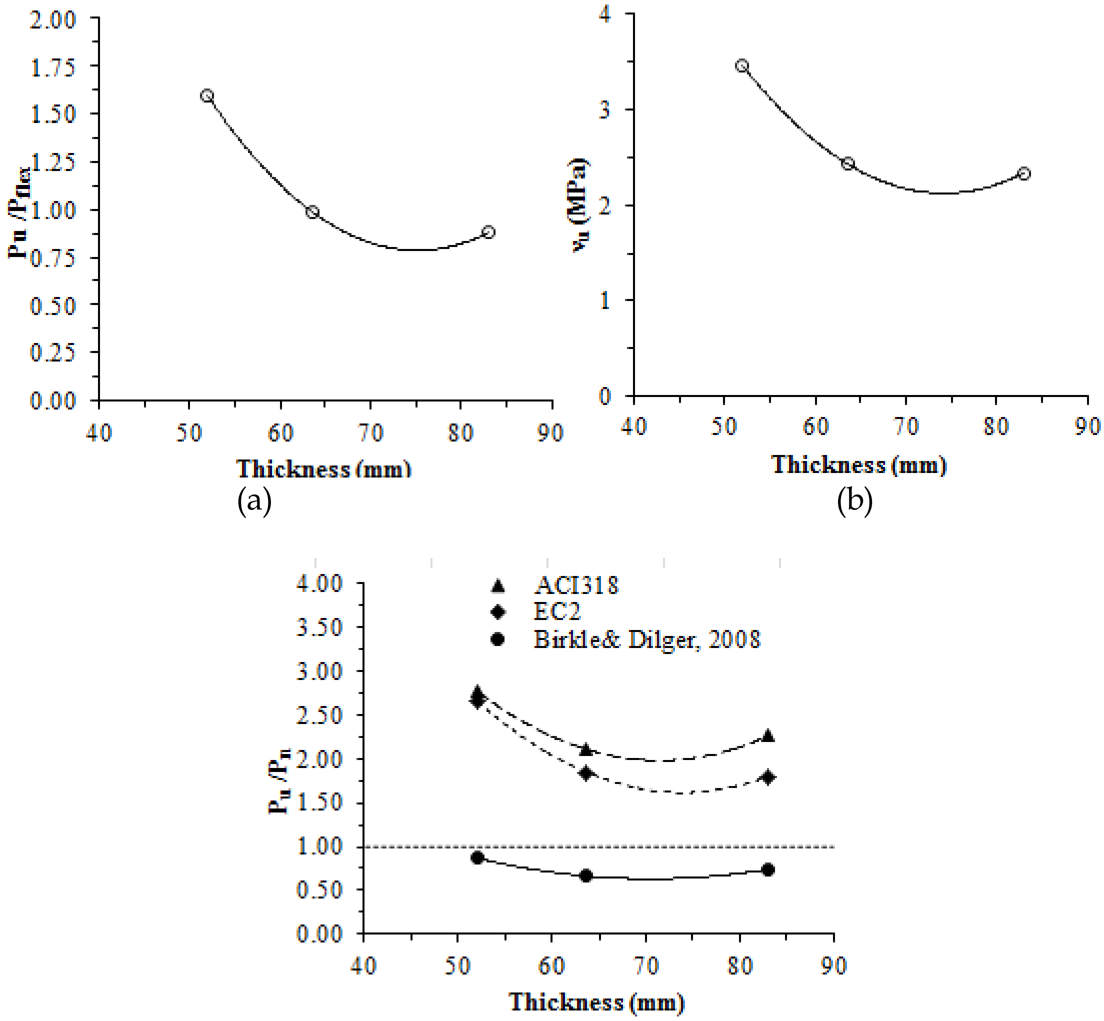
Punching Shear Strength

Table 3. summarized the test results. In spite of that f ´c of the normal concrete is higher than f ´c of the ECC, but the splitting strength (fsp) of the ECC were higher, it is shown that the correlation between the (fsp)to the square root of the f ´c was 0.59 which is close to correlation of the ACI318 [4] (0.556), while the correlation is increased 110 % for the ECC. This is not surprising because the ECC tends to form multi micro cracks between the first crack strain and the 1 % strain (Li, V.C.). The load required to initiate the cracks (Pcr) compared to ultimate load resistance (Pu) are increases with increasing the slab depth, the cracking load in ECC slabs are ranging between 7 and 14 % of the ultimate load, whereas the Pcr is initiated at 19 % of Pu for the specimen P (of normal concrete).

From the Table 3, it is shown that the slabs' strength increases with increasing the slab thickness, however, the flexural capacity are decreases (Figure 3a), that is lead to reduction in shear stress with increasing the slab thickness (see Figure 3b), this is agreed with Birkle and Dilger (Brikle & Dilger) finding. Comparing the ultimate strength with the nominal strength of the ACI318 (ACI318-14) and Eurocode 2 (EN1992-1-1) shows that these codes are conservative moreover; theses codes don't capture the effect of thickness on PVA-ECC. There are no differences between the two codes in prediction the punching shear for the V5, while the differences are increases with increasing the slab thickness. However, the proposed nominal strength by Birkle and Dilger (Brikle & Dilger) was not conservative and overestimated the ultimate resistance (see Figure 3c), but the latter is best considered the size effect than the codes' equation.

Table 3. Summary of the Test Results

Spce. Code	Age	Density	d	f_{sp}	f'_c	$\frac{f_{sp}}{\sqrt{f'_c}}$	P_{cr}	δ_{cr}	P_u	δ_u	$\frac{P_{cr}}{P_u}$	P_{flex}	$\frac{P_u}{P_{flex}}$
	Day	Kg/m^3	mm	MPa	MPa		kN	mm	kN	mm		mm	
P	45	2330	29.7	3.85	43.20	0.59	9.89	0.86	51.31	5.52	0.19	38.29	1.34
V5	49	1987	29.7	7.68	38.66	1.24	9.65	0.51	61.02	6.15	0.16	38.29	1.59
V6	48	1979	39.7	7.68	38.66	1.24	11.90	0.75	69.27	3.96	0.17	70.26	0.99
V8	40	2013	59.7	7.68	38.66	1.24	12.87	1.87	135.53	3.81	0.09	153.97	0.88



(c)

Figure 3. Effect Of Slab Thickness On (a) Flexural Capacity (b) Shear Stress (c) With Other Proposed Nominal Equations (ACI318-14, EN1992-1-1, Brikle & Dilger).

Load –Deflection Relationship

Figure 4. shows the deflection response under increasing monotonic loading, The loads are applied to the tested specimens up to failure, however, the curves show the response up to 50 % of the Pu, this is based on the authors experience, where the effect of tensile membrane action are included at this level, the deflections in Figure 4 are recorded from the LVDT placed at the center of slabs. It is shown that ΔP/Δδ of the PVA-ECC slabs are more than the slab of the normal concrete, moreover, ΔP/Δδ are decreases with decreasing the slab thickness. At the failure zone (beyond δu) It is showing that the load of the slabs of 60 and 80 mm (V6 and V8) are decreased sharply, this behavior also shows in specimen P (slab of normal concrete), whereas the slab V5 the load is gradually decreasing in the failure zone. Based on these premises, the ductility of the slabs is decreased significantly with increasing the slab thickness. Table 4 summarized the ductility of the tested slabs, the ductility refers to the efficiency of the materials to sustain the deformation before a collapse, the ductility quantified here in as a ratio of the deflection corresponding to 50 % of ultimate load to the deflection at first crack. From Table 4, it is clear that the ECC slabs show high ductility index than the slab of normal concrete, where the ductility index for V5 is more than that for P by 308 %, however, increasing the thickness of slab from 50 mm to 80 mm is reduced the ductility index by 25 %.

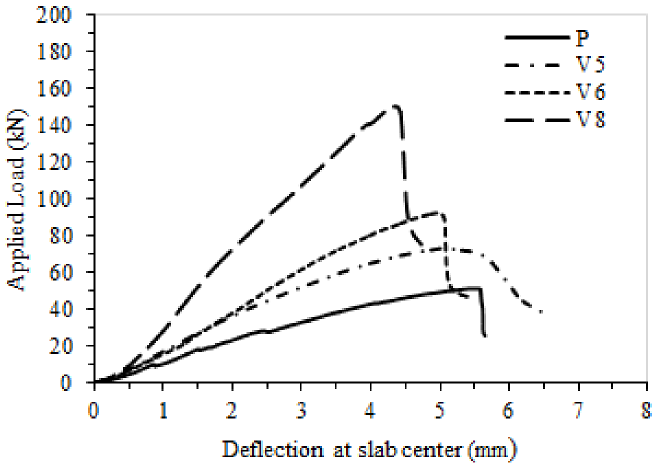


Figure 4. Load-Deflection Curves for ECC Reinforced Slabs

Table 4. Ductility And Failure Mode

Spec. Code	**d** mm	**P_u** kN	l_{cr}† mm	**μ**	**Failure Type**
P	29.7	51.31	2.5d	2.5	P+F
V5	29.7	61.02	2.7d	10.4	P+F
V6	39.7	69.27	1.9d	6.9	P
V8	59.7	135.53	1.4d	7.8	P

† l_{cr} is the distance from the column face to the punching shear crack in term of effective depth d

Cracks Pattern

The slabs designed to fail due to punching shear, the design applied to normal reinforced concrete in order to compare the effect of using high tensile and ductility materials. All slabs show the punching cone in deferent load levels. The important finding is that increasing the thickness is decreases the distance (lcr) from the column face to the punching circular crack. lcr is represented in term of d, where lcr is equal to 2.7 d in V5 this distance is reduced to 1.4 d in V8 with reduction of 48 % (see Table 4). That is means that the variation of the thicknesses is significantly affected the deformation.

Figure 5 shows the cracks patterns, where the failure of the ECC slabs are ranging between the uncompleted circle and completed circle, however, the slabs of 50 mm thickness of ECC and normal concrete shows radial cracks extended to edges of the slabs. Table 4 shows the type of failures. Moreover, it is recognised that the thicker slab shows more cracks than that thinner; this is because of the brittle behaviour of the thicker slab in addition to the congestion of the reinforcement bars.

CONCLUSIONS

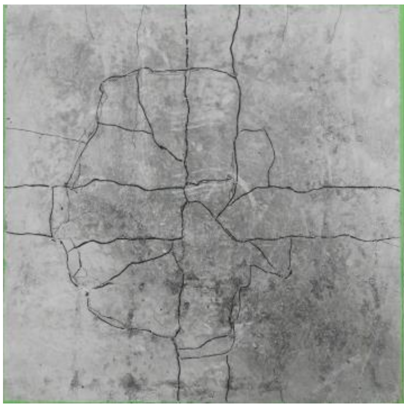
Tests on slabs made from PVA-ECC materials, and with 50, 60, and 80 mm thickness, the control slab of normal concrete is designed due to in punching shear. The important conclusions driven from the current work can be summarized as follows,

Increasing the slab thickness was increased the ultimate punching shear strength, moreover, reducing a flexural capacity of the section and the shear stress at distance of d/2.

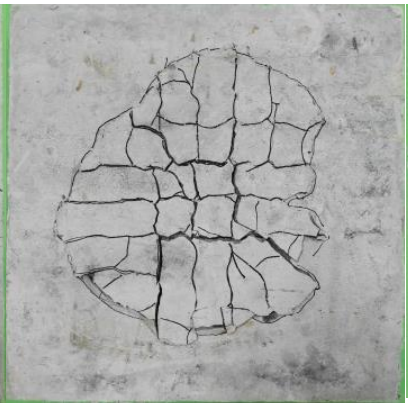
The total deformations are reduced with increasing the slab thickness, and the thicker slabs tend to fail due to punching shear.

The proposed codes equations [4] [5] of the nominal punching shear strength are significantly under estimated the tested slab, and not captured the effect of slab size.

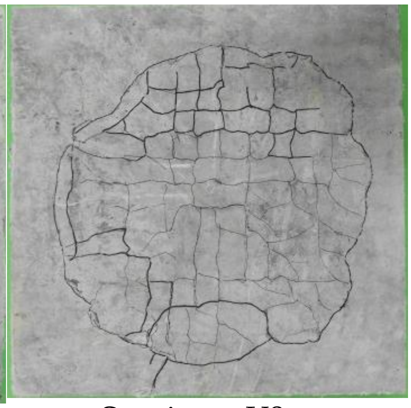
Using PVA-ECC materials are significantly enhanced the ductility of the slabs compare to the normal concrete slabs.



Specimen V5
Pu= 61.02 kN f'c = 38.66 MPa
d = 50 mm



Specimen V6
Pu= 69.27 kN f'c = 38.66 MPa
d = 60 mm



Specimen V8
Pu=135.53 kN f'c = 38.66 MPa
d = 80 mm

Specimen P
Pu= 51.31 kN f'c = 43.20 MPa
d = 50 mm

Figure 5. Cracks patterns of panels

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