Failure Characteristics and Critical Punching Perimeter of High Strength Concrete Panels

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ABSTRACT **- This research presents an experimental program for investigating punching shear strength of slabs, consisting of 27 high and normal strength concrete slabs. The test data from the experiment are analyzed and divided into three series primarily concerned with the effects of three variables on the punching strength of high-strength (HS) concrete slabs: the concrete strength, the slab depth and the column size and shape. The tests showed that the critical perimeter is located at a distance (1.5d) from the load area.**

KEYWORDS- **Punching, Shear, High Strength Concrete, Flat Slabs, Critical Path, and Effective Depth.**

1. INTRODUCTION

Punching shear is a phenomenon in flat slabs caused by concentrated support reactions inducing a cone shaped perforation starting from the top surface of the slab. Although generally preceded by flexural failure, punching shear is a brittle failure mode and the risk of progressive collapse requires a higher safety class in structural design.

The undesirable suddenness and catastrophic nature of punching failure are of concern to structural engineers. In this respect, the use of high-strength concrete improves the punching strength of HSC flat slabs and allows higher forces to be transferred.

In 1961, Moe [(1)] reported tests of twenty-eight 1.83 meter square slabs. The variables in Moe's tests are cleared through the following semi-empirical equation which was predicted form the experimental results.

Later in 1970, Herzog [(2)] derived a simple empirical formula to estimate the punching shear strength of slabs. He analyzed the results of fourteen previous investigators, and the main variables taken into consideration were flexural compressive steel ratio (ρ), steel yield strength (f_y) and compressive strength of concrete (f_c').

Regan [(3)] in 1981 developed an equation to calculate the punching shear capacity of reinforced concrete slabs. Regan's shear perimeter for rectangular columns was a rounded rectangle located (1.25 d) out from the column face, for circular columns it was the circular perimeter located (1.25d) from the column face.

In 1987, Rankin [(4)] developed a two-phase approach that classifies the punching failure as flexure and shear. First, the shear punching strength and the flexural punching strength are calculated. Then, the results are used to determine the failure mode.

In 1990, Gardner [(5)] reported tests of thirty circular slabs. The variables in Gardner's tests are concrete strength, steel ratio and slab thickness. He also made comparison with some researchers and code provision on punching shear capacity. Gardener concluded that the steel ratio in the region (3d) from the column should be of the order of 0.5 percent in each direction, and the spacing should be equal to the effective depth. He also found that the cube-root relationship between shear strength and concrete strength is preferable to the square-root relationship.

2. EXPERIMENTAL PROGRAM

2.1 MATERIALS

1. Cement; Ordinary Portland cements (OPC) was used in the experimental program. It is produced by Al-Sabe'a factory in Lebanon.
2. Fine aggregate (sand); Al-a'sela natural sand with maximum size of 4.75 mm was used throughout this work. The grading of the sand was conformed to the Iraqi specification No. 45/1984 [(6)].
3. Coarse aggregate; Crushed gravel from AL-Nibaey region was used throughout this work. According to the recommendations of ACI 221.4R-93 [(7)] for mix selection of high performance concrete, the maximum size of 10 mm (3/8 in.) for the crushed gravel was selected.
4. Superplasticizer; High range water-reducing admixture called SP-1 was used throughout the experimental work. The superplasticizer was produced by (Al-AZRAK Company, Jordan) and it is complied with ASTM C494 type A&F as described in the manual of the product.
5. Mixing water; Tap water was used for casting and curing all the specimens.
6. Steel reinforcing mesh; One size of normal strength steel wires was used. Wires of size (ϕ 2.5mm) used as a bottom mesh reinforcement for the two phases of research (punching strength and long-term deflection) with 5 mm concrete cover. Yield strength of the wires was determined by tensile test. Results of test showed that the yield strength of the wires of (ϕ 2.5mm) equal to 420 MPa. The number of wires in the punching panels was (15) wires in each direction.
7. Molds fabrication; Steel angles were used to fabricate the molds. Four profiled steel angles are assembled using bolts passing through holes in each corner. The assembled test frame is then made to be stood up on a steel base. The base plate is connected firmly to the frame by several bolts through the length of steel angles.

2.2 Mix design

According to the recommendations of the ACI 221.4R 93 [7] several trial mixes were made. Reference concrete mixture was designed to give a 28-day characteristic compressive strength of 64 MPa. The cement content was 550 kg/m^3, water/cement ratio was 0.32, Vebe time was (6) second, superplasticizer was (1.4%) by weight of cement, and proportions of mix was found to be {1:1.21:1.8} by weight.

2.3 Mixing, casting and curing procedure

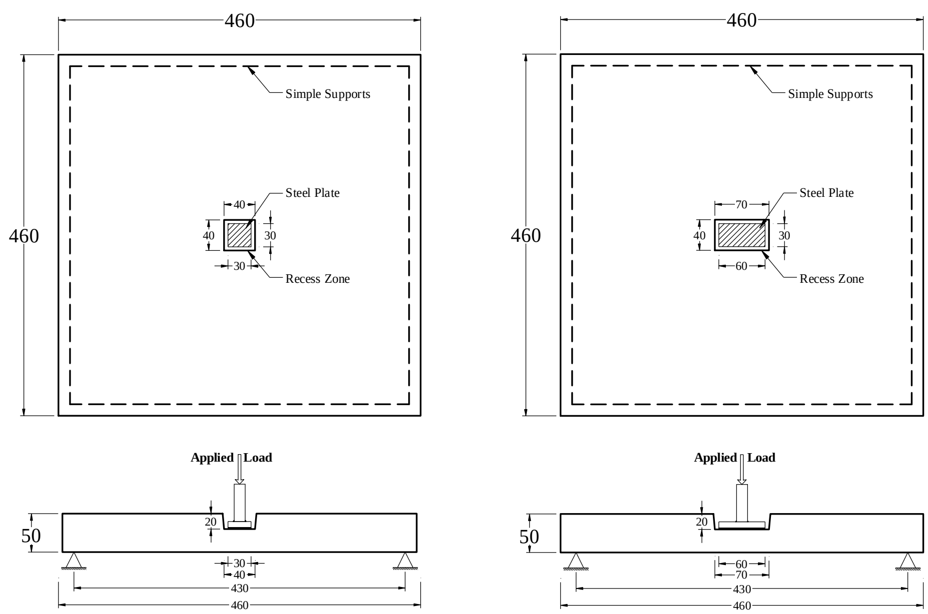
Corresponding to the different types of concrete mixes described previously, nine groups, each group consist of three panels of (460×460×50) mm were cast. These groups are marked as (HS1, HS2,…, and HS7) with two groups of normal strength concrete are marked as (NS1 and NS2), as shown in Table (1). Furthermore, corresponding to each slab, three companion (100 mm) cubes of concrete were cast. The mixing procedure according to the ACI committee 211 [8] was followed as described below:

A. *Before mixing, all quantities were weighed and packed in clean containers.*
B. *The weighed superplasticizer was added to the measured mix water taking into account the percentage of water contained in the weighted superplasticizer.*
C. *Saturated surface dry crushed gravel, dry sand, and cement were added to the rotary drum mixer of (0.1 m^3 volume capacity) and (15 r.p.m.) mixing speed. The rotary drum mixed the dry materials for several minutes before adding the water to the mix gradually during two minutes.*

Before placing the concrete in the molds, steel wire mesh reinforcement for each slab were placed in the molds. Each slab is reinforced with one steel mesh of (15ϕ2.5mm Each Way), distributed in the bottom face. Recess has been introduced to ensure the slabs fail in punching before flexure. Figure (1) shows details of the slabs used in this work.

2.4 Compressive Strength Testing

Based on the British Standard (BS1881-Part 4 1983) [9], the compressive strength test was carried out using FORNEY compression machine on (100 mm cube) specimens. The compressive strength was considered as the average values for three specimens. The result of the test is shown in Table (1).



(a) Square Column (b) Rectangular Column

Figure (1) Details of the punching slabs under test [All dimensions in (mm)]

3. Test variables and specimen series

Three variables are investigated to show their effects on the shear strength of the slab models. These are:

1. The compressive strength of the concrete
2. Slab Thickness.
3. Column shape; The ratio of short to long sides of the column cross-sectional area a/b having two values of (0.5) and (1.0).

Three series of normal and high strength reinforced concrete square slabs with dimensions of (460×460×50) mm are simply supported at four edges with corners secured to be not free to rise using a special supported steel frames made for this purpose, so that a clear panel of (430×430) mm was maintained to be loaded by means of concentric steel column with a height of (150 mm).

According to this classification, twenty seven slab specimens were manufactured and tested upon which the test data and results of this investigation fall. All characteristics and details of these test specimens are listed in table (1).

Table (1) Detailed characteristics of slab specimen

Series No.	Slab designation	ID	Cube comp. stren. MPa	Av. comp. Stren. MPa	Slab Thick. mm: Flexural thick.	Slab Thick. mm: Punching thick.	Column: Cross Section	Column: a / b	Recess Size	Load (kN): At ultimate	Load (kN): Av.
ONE	HS1	*HS1-1*	66.8	75.4	43	26	30 × 30	1	40 × 40	12.4	12.67
		HS1-2	74.5		43.5	26.5				13.1	
		HS1-3	84.8		43.5	23.5				12.5	
	HS2	*HS2-1*	55	64	43	25				11.5	11.77
		HS2-2	65		47.5	28				10.6	
		HS2-3	72		45	27				13.2	
	HS3	*HS3-1*	50.1	54.9	46	25				10.5	10.87
		HS3-2	51.4		44.5	26.5				11.8	
		HS3-3	63.2		44	24				10.3	
	NS1	*NS1-1*	39	36.1	43.5	25.5				10.1	10.17
		NS1-2	37.3		45	27				9.8	
		NS1-3	32		47	24				10.6	
TWO	HS4	*HS4-1*	89	94.2	45	28	60 × 30	0.5	70 × 40	18.8	17
		HS4-2	93		43.5	26				16.4	
		HS4-3	100.5		44.5	28				15.8	
	HS5	*HS5-1*	90.5	86.2	46.5	27.5				14.5	14.8
		HS5-2	86		44	27				15.7	
		HS5-3	82		47	27				14.2	
	HS6	*HS6-1*	65.4	61.7	47	29				12.8	13.1
		HS6-2	54.7		45	26.5				13	
		HS6-3	64.9		45	26				13.5	
	NS2	*NS2-1*	36.2	33	48	25				11.1	11.53
		NS2-2	33.5		45.5	27				12	
		NS2-3	29.2		47.5	25				11.5	
THREE	HS7	*HS7-1*	64.6	62.3	44	44	40 × 40	1	w/o recess	29.2	29.23
		HS7-2	64.2		43	43				28.4	
		HS7-3	58		47	47				30.1	

Note: $f_c^{/} = 0.83 f_{cu}$ for HSC > 50 MPa, $f_c^{/} > 0.8 f_{cu}$ and reaches to $0.89 f_{cu}$ for HSC=80 MPa [10]

4. Failure Characteristics

4.1 Observation of Failure

Punching shear failure had occurred suddenly in all the tested slabs. There was no sign of warning before the occurrence of failure, except the rapid movement of the dial gauge.

In the case of sudden failure, the dial gauge faced a sudden shock and moved from its position in some slabs, especially those slabs of group HS2 and slabs of group HS7.

4.2 Shape of the Failure Zone

It was observed that the shape of the failure zone in plan is ranging from a circle to a square with round corners. The shape can be modelled similar to that proposed by the ACI 318-11 [11]. Figure (1) shows shapes of the failure zones of the tested slabs.

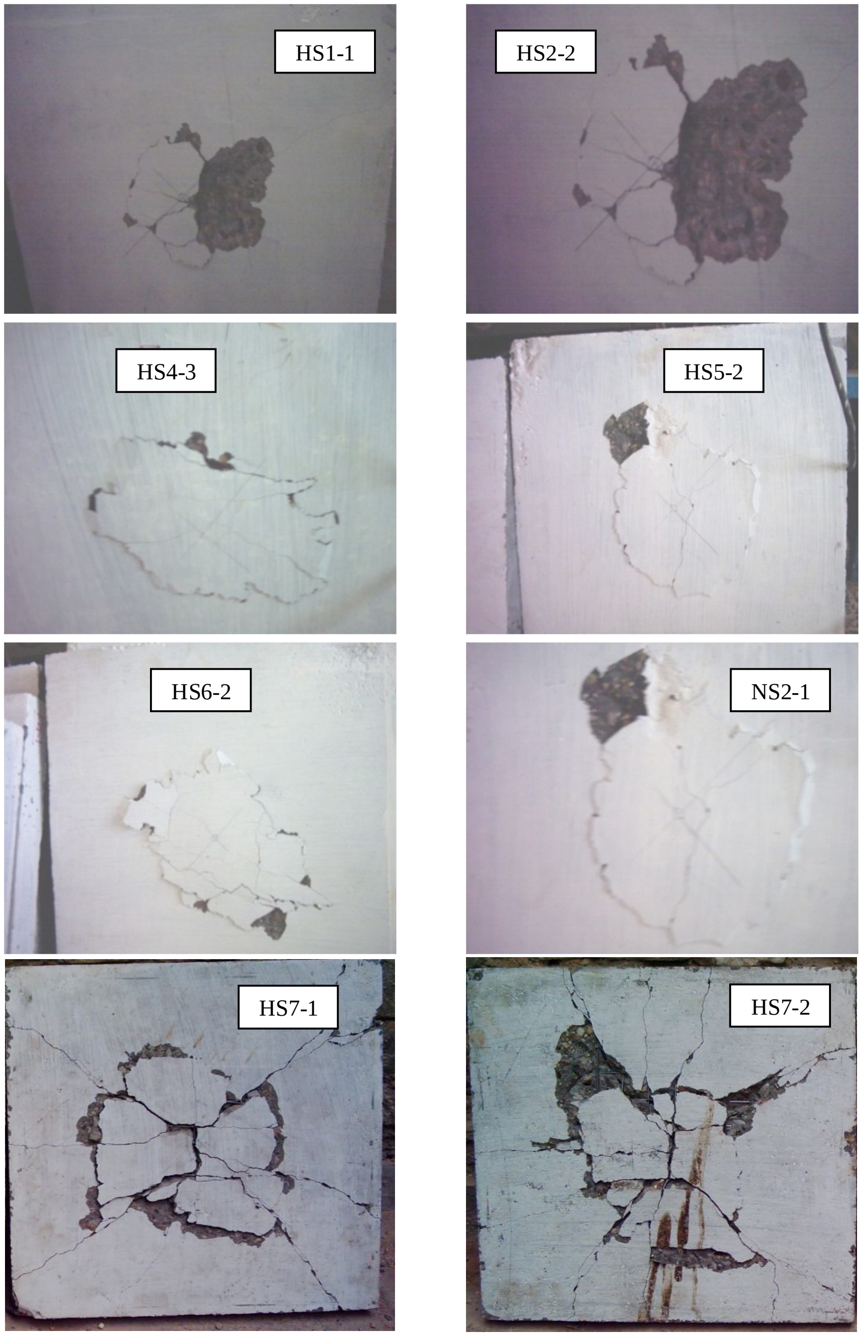


Figure (1) Sample of modes of failure of some tested slabs

4.3 Size of the Failure zone

The areas of the punching failure zones were measured by using AutoCAD program, and their perimeters were also measured.

The average measured area for each group is shown in Table (2). It can be noted that the size of the failure zone decreased by decreasing compressive strength. The size of the failure zone increased by increasing column dimension ratio.

It must be noted that this area included the spalled portion outside the shear crack. This portion was very large in slabs of group HS7 as compared to the other groups.

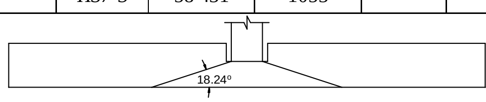
5. Failure Angle

The failure angles of the punching pyramid were measured by indicating the dimensions of crushed zone at the centre line passing through the loaded area. It was observed that the angle of failure was about 18.24^{o} with respect to horizontal for slabs of group HS1. The angle was gradually decreased by increasing column side, and the angle was about 17.77° in slabs of group HS4.

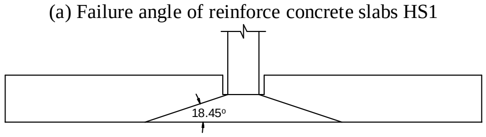
Although the failure angle was less in slabs with high strength concrete strength, the failure pyramid that was pushed out in slabs has a much wider base than that in slabs with less compressive strength as shown in Figure (2).

Table (2) Details of the measured area in the slabs that failed in punching

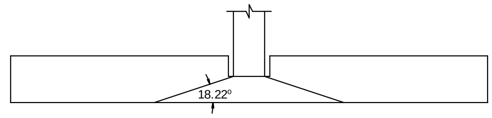
Series No.	Slab designation	ID model design-ation	Measured area mm^2	Measured perimeter mm	Av. area mm^2	Average perimeter mm
ONE	HS1	*HS1-1*	32 523	705	30 582	650
		HS1-2	29 750	606.6		
		HS1-3	29 473	638.4		
	HS2	*HS2-1*	28 092	637.2	28 777	648
		HS2-2	25 340	609.5		
		HS2-3	32 900	698.1		
	HS3	*HS3-1*	28 674	620	28 446	658
		HS3-2	26 841	654		
		HS3-3	29 823	701		
	NS1	*NS1-1*	24 610	675	27 344	619
		NS1-2	29 095	577		
		NS1-3	28 326	605		
TWO	HS4	*HS4-1*	44 161	837.4	40075	787
		HS4-2	39 189	768.33		
		HS4-3	36 876	756		
	HS5	*HS5-1*	35 435	725.9	39409	769
		HS5-2	47 916	850		
		HS5-3	34 876	731		
	HS6	*HS6-1*	38 866	751.9	38977	771
		HS6-2	38 290	787.2		
		HS6-3	39 775	773.7		
	NS2	*NS2-1*	30 710	695	33102	649
		NS2-2	34 165	617		
		NS2-3	34 431	635		
THREE	HS7	*HS7-1*	57 890	980	58937	1050
		HS7-2	60 491	1118		
		HS7-3	58 431	1053		



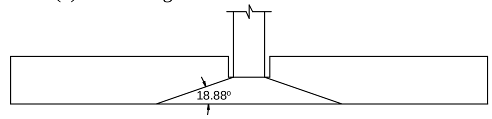
(a) Failure angle of reinforce concrete slabs HS1



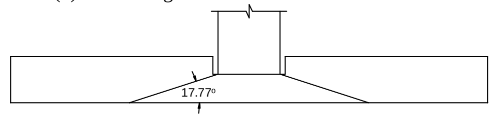
(b) Failure angle of reinforce concrete slabs HS2



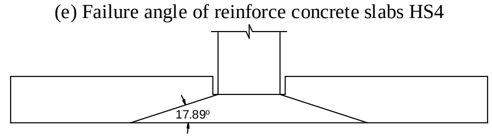
(c) Failure angle of reinforce concrete slabs HS3



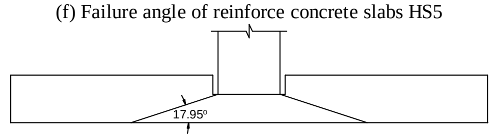
(d) Failure angle of reinforce concrete slabs NS1



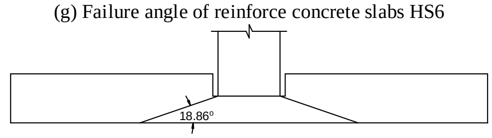
(e) Failure angle of reinforce concrete slabs HS4



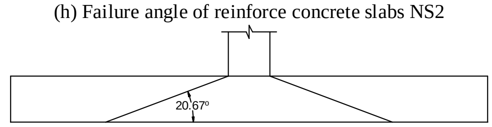
(f) Failure angle of reinforce concrete slabs HS5



(g) Failure angle of reinforce concrete slabs HS6



(h) Failure angle of reinforce concrete slabs NS2



(i) Failure angle of reinforce concrete slabs HS7

Figure (2) Estimated failure angles for the tested slabs

6. Critical Section Perimeter

The distance of the critical section for the slabs tested in this investigation is considered as half the distance between the end of failure surface and the face of the column. The calculated distances are based on the measured area. Figure (3) shows the method used to calculate the critical sections for the tested slabs in this investigation. Table (3) reports the calculated distance.

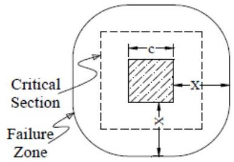
Previous research (11) showed that the critical section perimeters ranged from (1.16 h) to (1.4 h) for plain concrete slabs.

Tuan (12) showed that the critical section perimeters equal to (2d) for high strength concrete and this conformed to CEB-FIP MC-93 (13).

Both the ACI code (11) and the Rankin's approach (4) assume that the control perimeters is located at a distance of 0.5 times the effective depth from the edge of load, while the BS8110 code (9) considers a larger control perimeter, 1.5d.

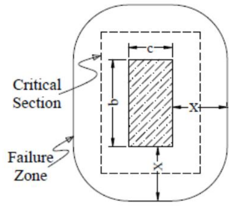
The recommendations given in Euro Code 2 (2005) regarding punching shear resistance are largely based on section 6.4.3 in the CEB-FIP Model-Code (13) on Concrete Structures (1993). The recommendations use a conventional formulation identical to the monodirectional case of a beam although a control perimeter is considered instead of a beam width. The control perimeter is defined as the assumed crack periphery on the top surface of the slab and is in EC2 taken as

$$A = c^2 + 4cX + \pi X^2$$
$$\pi X^2 + 4cX + (c^2 - A) = 0$$
$$X = \frac{-4c + \sqrt{(4c)^2 - 4\pi(c^2 - A)}}{2\pi}$$



(a) For Square Column

$$A = c.b + 2c.X + 2b.X + \pi X^2$$
$$A = c.b + x.(2c + 2b) + \pi x^2$$
$$\pi X^2 + (2c + 2b).X + (c.b - A) = 0$$
$$X = \frac{-(2c+2b) + \sqrt{(2c+2b)^2 - 4\pi(c.b - A)}}{2\pi}$$



(b) For Rectangular Column

Figure (3) Method used to calculate critical section

Critical section is assumed at a distance X/2 from face of column.
Here: A= *measured area in mm^2*, X= *distance of failure surface*
c *and* b = *column sides length*

Table (3) Details of calculation of 'X' distances in the slabs that failed in punching

Ser No.	Slab designa-tion	ID model design-ation	Measured area mm^2	X (mm)	$\frac{X}{2d}$	Av.
ONE	HS1	*HS1-1*	32523	83.03	1.66	1.50
		HS1-2	29750	78.62	1.40	
		HS1-3	29473	78.16	1.45	
	HS2	*HS2-1*	28092	75.88	1.46	1.53
		HS2-2	25340	71.15	1.34	
		HS2-3	32900	83.62	1.78	
	HS3	*HS3-1*	28674	76.85	1.54	1.52
		HS3-2	26841	73.76	1.39	
		HS3-3	29823	78.73	1.64	
	NS1	*NS1-1*	24610	69.85	1.37	1.46
		NS1-2	29095	77.54	1.44	
		NS1-3	28326	76.27	1.59	
TWO	HS4	*HS4-1*	44161	90.95	1.62	1.56
		HS4-2	39189	84.14	1.62	
		HS4-3	36876	80.83	1.44	
	HS5	*HS5-1*	35435	78.72	1.43	1.55
		HS5-2	47916	95.85	1.78	
		HS5-3	34876	77.88	1.44	
	HS6	*HS6-1*	38866	83.69	1.44	1.55
		HS6-z2	38290	82.87	1.56	
		HS6-3	39775	84.97	1.63	
	NS2	*NS2-1*	30710	71.47	1.43	1.47
		NS2-2	34165	76.82	1.42	
		NS2-3	34431	77.22	1.54	
THREE	HS7	*HS7-1*	57890	117.16	1.33	1.33
		HS7-2	60491	120.16	1.40	
		HS7-3	58431	117.79	1.25	

7. Conclusions

1. It was observed that the shape of the failure zone in plan is ranging from a circle to a square with round corners.
2. The size of the failure zone decreased by decreasing compressive strength. The size of the failure zone increased by increasing column dimension ratio. The average area has increased (12 %) when the compressive strength increased from (36.1 MPa) to (75.4 MPa) for square loading. The increase in area is found to be (21 %) in rectangular loading area when the compressive strength increased from (33 MPa) to (94.2 MPa).
3. The failure angles of the punching pyramid were measured by indicating the dimensions of crushed zone at the centre line passing through the loaded area. It was observed that the angle of failure was about 18.24 with respect to horizontal for slabs of group HS1. The angle was gradually decreased by increasing concrete strength to about 17.77 in slabs of group HS4, the angle was decreased to about 17.890 in slabs of group HS5 by increasing column side ratio, and the angle was about 20.67 in slabs of group HS7.
4. The critical path distance shows slight increase when the concrete strength increased. The investigations show that the distance increased 1.5% for each 20 MPa increasing in concrete strength.
5. The tests show that the average critical perimeter in rectangular columns of sides ratio 2, is larger than the square columns perimeter by 2.5%.

(2.0 d) from the face of the support, where (d) denotes the effective slab depth. However, it is important to bear in mind that the control perimeter does not predict the actual punching cone as it is dependent on detailing.(14)

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