Bearing strength of reinforced high strength concrete

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This paper presents results from an extensive experimental investigation on 57 plain and reinforced concrete specimens having the shape of blocks loaded over a limited area in order to study the bearing strength of high strength concrete. Both concentric and eccentric square, rectangular, and strip loading patterns were considered. The effect of several significant factors on the ultimate bearing strength of high strength concrete were detected such as block height, block cross section size, and percentage of transverse reinforcement. Results revealed that the behavior of high strength concrete in bearing is significantly different than that of normal strength concrete. Also, it was concluded that the inclusion of transverse reinforcement in high strength concrete blocks is important since it changed the nature of bearing failure from an explosive, sudden failure to a relatively ductile mode of failure and prevented the sudden loss in the bearing strength. The experimental data obtained were used to develop an empirical formula for the estimation of the ultimate bearing strength of high strength concrete. The proposed formula takes into account the effect of the ratio of total area to loaded area, width to height ratio, percentage of transverse reinforcement, and the eccentricity of the load in both directions. Finally, the experimental results for the ultimate bearing strength of some of the blocks tested were compared to those predicted by codes of practice and the proposed empirical formula. The comparison revealed that code predictions are conservative. However, such equations can be used safely for the estimation of the ultimate bearing strength of high strength concrete.

يقدم هذا البحث نتائج دراسة معملية مكثفة شملت ٥٧ عينة من الخرسانة العادية والمسلحة لدراسة مقاومة الإرتكاز للخرسانة عالية المقاومة. وقد تم دراسة حالات الأحمال المركزية واللامركزية المربعة والمستطيلة والشريطية. وتم إستنتاج تأثير عوامل هامة كثيرة على مقاومة الإرتكاز القصوى للخرسانة عالية المقاومة مثل إرتفاع العينة ومقاس مقطع العينة والنسبة المئوية لحديد التسليح العرضي. وقد أظهرت النتائج أن سلوك الخرسانة عالية المقاومة فى الإرتكاز يختلف إختلافا كبيرا عن سلوك الخرسانة عادية المقاومة. أيضا أظهرت الدراسة أهمية وجود حديد التسليح العرضى فى العينات فى حالة الخرسانة عالية المقاومة حيث أن وجود الحديد العرضى أدى إلى تغير طبيعة الإنهيار المفاجيء للعينات فى الإرتكاز ومنع الفقدان المفاجيء لمقاومة الإرتكاز. وقد إستخدمت النتائج المعملية فى عمل معادلة تجريبية لحساب مقاومة الإرتكاز القصوى للخرسانة عالية المقاومة. هذه المعادلة المقترحة تأخذ فى الإعتبار تأثير نسبة المساحة الكلية للعينة إلى المساحة المحملة ، نسبة العرض إلى الإرتفاع ، النسبة المئوية لحديد التسليح العرضى ،وتأثير لا مركزية الأحمال فى الإتجاهين. أخيرا تم عمل مقارنة بين النتائج المعملية لمقاومة الإرتكاز القصوى لبعض العينات المختبرة مع نتائج المعادلات المعطاه فى بعض المواصفات وأيضا مع نتائج المعادلة التجريبية المقترحة. وقد أظهرت المقارنة أن معادلات المواصفات تعطى نتائج أقل من النتائج المعملية. على الرغم من هذا فانه يمكن إستخدام هذه المعادلات بأمان لحساب مقاومة الإرتكاز القصوى للخرسانة عالية المقاومة.

Keywords: Bearing strength, High strength concrete, Eccentricity, Reinforced concrete, Transverse reinforcement.

1. Introduction

An accurate design of many types of concrete members such as girder bearings, hinges, and foundation blocks require a good understanding of the concrete bearing strength. The behavior of non-flexural regions in concrete structures is a complex function of the non-homogeneous behavior of the reinforced concrete composite (Foster and Rogowsky [1]). When a local load is applied to a concrete block, the confining pressure of the concrete surrounding the contact area increases the resistance of the material in a manner similar to that observed in a triaxial compression test. Generally, the failure of the material occurs by splitting or shearing along one or several rupture surfaces, depending on the magnitude of the confining pressure. Based on that, the value of the bearing strength of concrete is taken by codes of practice (ECP [2]) and the ACI 318 [3] ranging between the concrete compressive strength and twice that value, depending on the ratio of the loaded area to the total area. However, these values of bearing strength are extremely conservative.

The previous investigations found in the literature do not cover all the important aspects of the problem of bearing. Hawkins [4] concluded that any increase in the bearing capacity above the compressive strength of concrete is directly dependent on the angle of internal friction. He recommended that the concrete in the bearing zone should be densely compacted and the air voids and shrinkage cracks kept to minimum. Ahmed et al. [5] studied experimentally the effect of using different classes of lateral reinforcement, varying from a well-anchored reinforcement to poorly detailed reinforcement, on the bearing capacity of concrete blocks. They concluded that the failure of the specimens was of a tensile nature and the variations in the bearing strengths were more closely related to the tensile strength of concrete than the cube compressive strength. They also indicated the beneficial effect of providing lateral reinforcement in increasing the failure bearing stresses of concrete.

Soroushian et al. [6] indicated that the bearing strength of concrete increases with increasing concrete strength and concrete cover normal to the direction of bearing action. Soroushian and Bayasi [7] concluded that the presence of fibers in the top layer of a concrete block under the bearing area slightly increases the strength and significantly improves the ductility of failure of concrete under bearing stresses. Ahmed et al. [8] pointed out that increasing the percentage of lateral reinforcement reduces the expansion due to the alkali-silica reaction (ASR). They also concluded that the ASR significantly reduces the bearing strength of concrete. Foster and Rogowsky [1] presented a number of two-dimensional plane stress finite element analyses in order to examine the transverse strain distributions of concrete under concentrated loads. They concluded that if,the transverse reinforcement is located for the greatest efficiency, savings in the quantity required to carry bursting forces can be obtained.

1.1 The required research

From the above presented available previous investigations, it is clear that there is a need for more detailed experimental investigations in order to cover all the important aspects of the problem of bearing strength of concrete. It was found that previous researches have concentrated on concentrically loaded plain concrete specimens. Most of these investigations have considered small size specimens such as 6 in concrete cubes or cylinders. However, the effect of other important variables are not well covered in the literature such as: (i) the effect of the dimensions of the specimen cross-section; (ii) the effect of specimen height relative to the dimensions of the cross-section; (iii) the effect of ratio of loaded area to the total area of specimen; (iv) the effect of the eccentricity of the loaded area; (v) the effect of providing transverse reinforcement; and, (vi) the effect of the percentage of such transverse reinforcement.

Recently high strength concrete is being widely used in the construction industry in order to increase the strength to dead weight ratio of reinforced concrete structures. High strength concrete may be used to achieve the economic use of space and durable structures. High strength concrete is defined by the ACI 318 [3] as concrete with cylinder compressive strength greater than 40 MPa No research efforts were directed towards the study of the bearing strength of high strength concrete. Both the Egyptian Code of Practice [2] and the ACI 318 [3] present empirical equations for the calculation of the bearing strength of concrete. The equations presented by the codes were calibrated using results from testing normal strength concrete specimens. Therefore, the validity of such empirical equations in the case of high strength concrete is questionable. Furthermore, these equations neglect the effect of several important factors on the ultimate bearing strength of concrete.

1.2. The current research

In this paper, an extensive experimental investigation is conducted in order to study the bearing strength of plain and reinforced high strength concrete. The experimental investigation included casting and testing 57 specimens up to failure. All the specimens tested were in the shape of blocks loaded over a limited area. Many variables were studied through the experimental investigation such as: (i) size of block cross-section; (ii) height of block; (iii) size of loading plate; (iv) eccentricity of loading plate; and, (v) amount of transverse reinforcement. For all tested blocks the initiation and propagation of cracks were observed and the cracking loads were recorded. Also, failure loads and modes of failure were observed and recorded. Furthermore, the experimental data obtained was used to develop an empirical formula for the estimation of the ultimate bearing strength of high strength concrete. The formula takes into account all the important factors affecting the ultimate bearing strength of concrete. Finally, the experimental results for the ultimate bearing strength of some of the blocks tested were compared to those predicated by codes of practice and the proposed empirical formula.

2. Experimental program

The effect of many important variables on the bearing strength of high strength concrete were studied through an extensive experimental program. The experimental program included casting and testing of 57 plain and reinforced high strength concrete specimens, all having the shape of blocks loaded over a limited area. The 28-day concrete cube compressive strength f_{cu} ranged between 73 N/mm^2 and 76.5 N/mm^2.

2.1. *Dimensions, reinforcement details, and loading patterns for tested blocks*

The tested concrete blocks were divided into three main groups namely GS1, GS2, and GS3. Main group GS1 included 21 blocks, all having cross-section dimensions of 200 mm. x 200 mm. and a height of 300 mm. Main group GS1 was divided into three sub groups namely GS1N, GS1R1, and GS2R2. Each sub group included 7 blocks. Reinforcement details for tested blocks in the three main groups are shown in Fig. 1. The seven blocks included in each sub group were tested under seven different loading patterns namely P1, P2, P3, P4, P5, P6, and P7, as shown in Fig. 2. All the loading plates used were made of mild steel having a thickness of 20 mm.

The 21 blocks included in main group GS2 were very similar to those included in main group GS1, except that the height of blocks in the case of GS2 was increased to 400 mm, compared to 300 mm. for group GS1. The main purpose of testing blocks in main group GS2 is to study the effect of block height on the bearing strength of plain and reinforced high strength concrete. The dimensions of the blocks cross-section were increased for the 15 blocks included in main group GS3 to 250 mm. x 250 mm. All the blocks included in main group GS3 had a height of 300 mm. The main purpose of group GS3 was to detect the effect of cross-section size on the bearing strength of plain and reinforced high strength concrete. The blocks included in main group GS3 were tested under five different loading patterns P1, P2, P3, P4, and P5, as shown in Fig. 3. Tables 1, 2, and 3 summarize the details of tested high strength concrete blocks included in main groups GS1, GS2, and GS3 respectively.

2.2. *Test procedure*

All high strength concrete blocks considered in the experimental program were tested using a 3000 kN testing machine. The lower face of each concrete block rests directly on the lower platen of the testing machine whereas the upper platen of the machine bores directly on the steel bearing plate, as shown in Fig. 4. The load was applied in increments of 25 kN up to the failure of each block. For all tested blocks the initiation and propagation of cracks were observed and the cracking loads were recorded. Also, failure loads and modes of failure were observed and recorded.

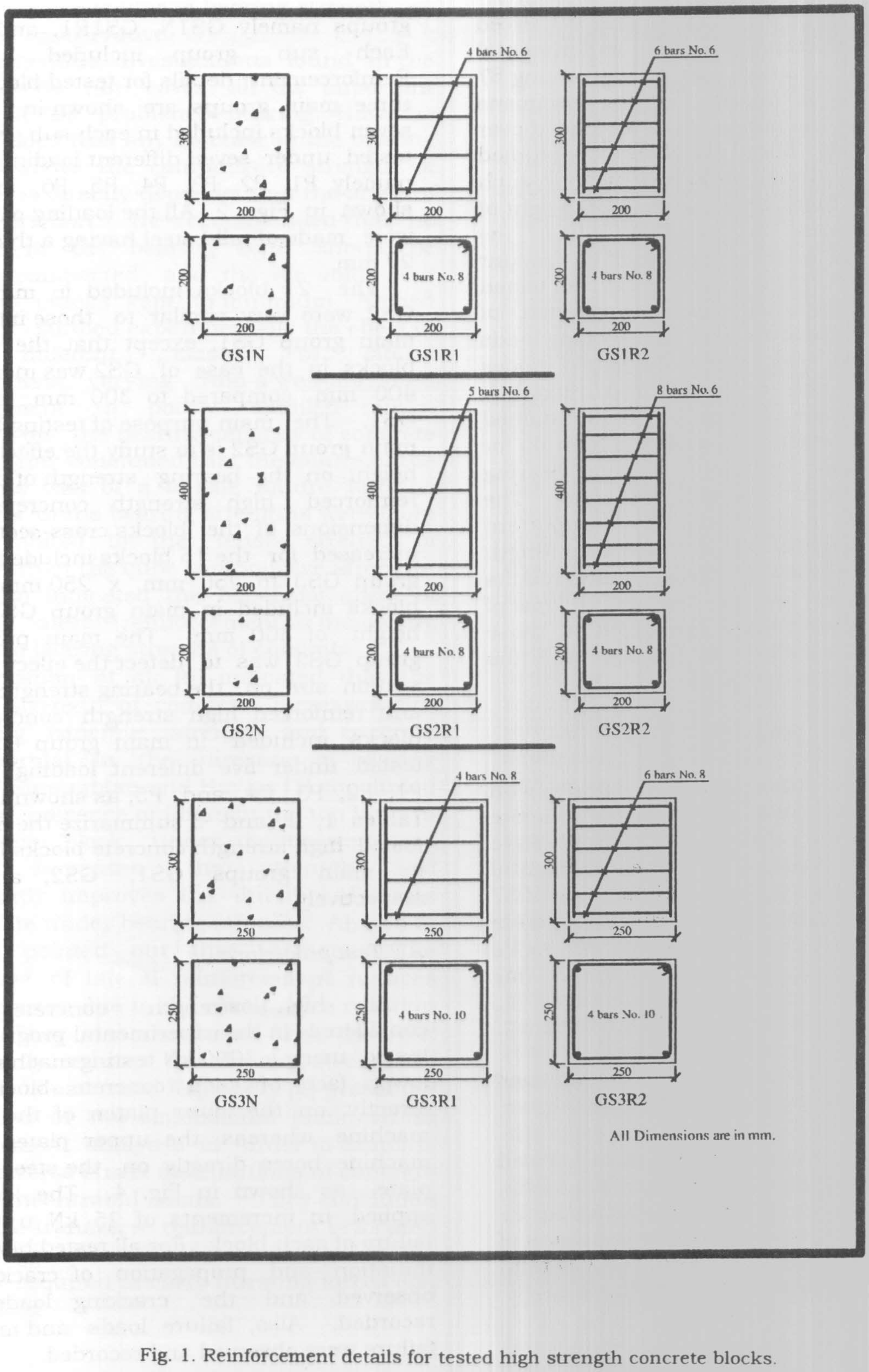

Fig. 1. Reinforcement details for tested high strength concrete blocks.

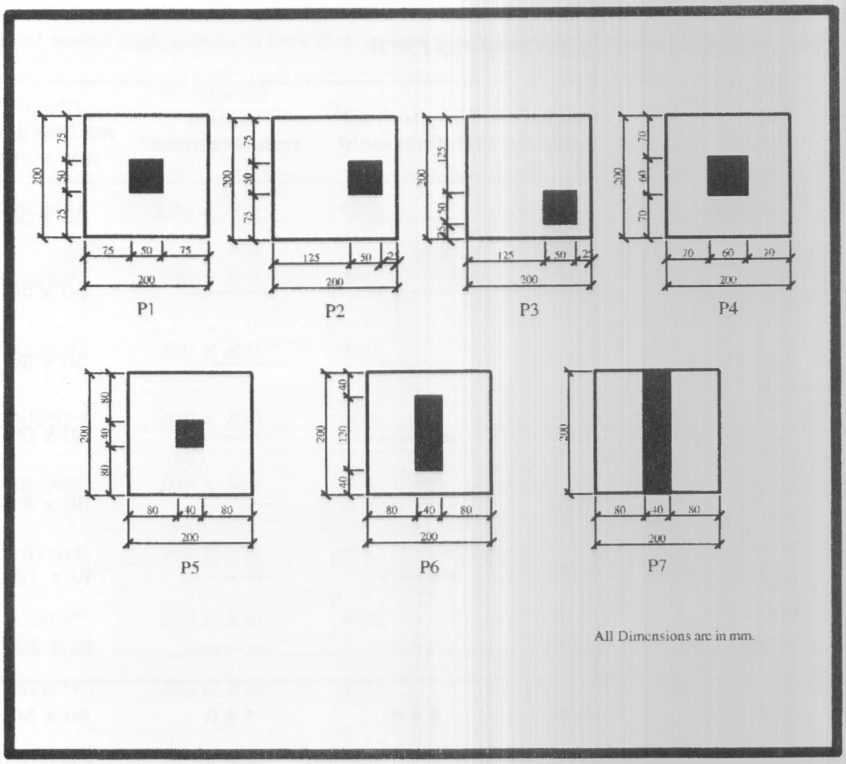

Fig. 2. Loading patterns for tested high strength concrete blocks groups GS1 and GS2.

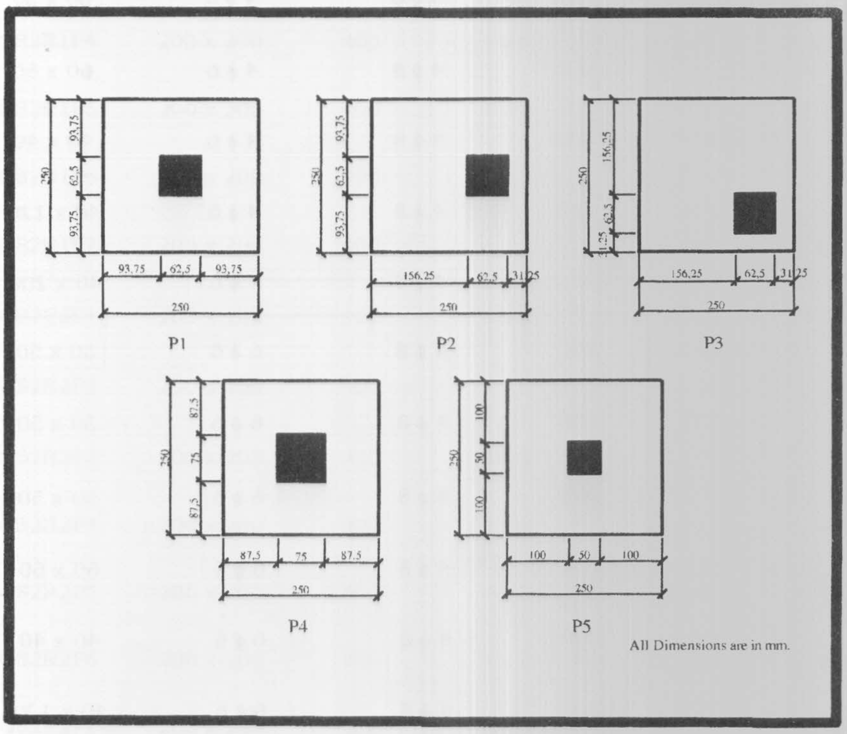

Fig. 3. Loading patterns for tested high strength concrete blocks group GS3.

Table 1. Details of tested high strength concrete blocks group (GS1).

Sub group	Block	Dimensions of cross-section mm x mm	Height mm	Longitudinal reinforcement	Lateral reinforcement	Size of loading plate mm x mm	Location of loading plate
GS1N	GS1NP1	200 x 200	300	---------	---------	50 x 50	Concentric
	GS1NP2	200x 200	300	---------	---------	50 x 50	Eccentric e_x = 50.0 mm e_y = 00.0 mm
	GS1NP3	200 x 200	300	---------	---------	50 x 50	Eccentric e_x = 50.0 mm e_y = 50.0 mm
	GS1NP4	200 x 200	300	---------	---------	60 x 60	Concentric
	GS1NP5	200 x 200	300	---------	---------	40 x 40	Concentric
	GS1NP6	200 x 200	300	---------	---------	40 x 120	Concentric
	GS1NP7	200 x 200	300	---------	---------	40 x 200	Concentric
GS1R1	GS1R1P1	200 x 200	300	4 ϕ 8	4 ϕ 6	50 x 50	Concentric
	GS1R1P2	200 x 200	300	4 ϕ 8	4 ϕ 6	50 x 50	Eccentric e_x = 50.0 mm e_y = 00.0 mm
	GS1R1P3	200 x 200	300	4 ϕ 8	4 ϕ 6	50 x 50	Eccentric e_x = 50.0 mm e_y = 50.0 mm
	GS1R1P4	200 x 200	300	4 ϕ 8	4 ϕ 6	60 x 60	Concentric
	GS1R1P5	200 x 200	300	4 ϕ 8	4 ϕ 6	40 x 40	Concentric
	GS1R1P6	200 x 200	300	4 ϕ 8	4 ϕ 6	40 x 120	Concentric
	GS1R1P7	200 x 200	300	4 ϕ 8	4 ϕ 6	40 x 200	Concentric
GS1R2	GS1R2P1	200 x 200	300	4 ϕ 8	6 ϕ 6	50 x 50	Concentric
	GS1R2P2	200 x 200	300	4 ϕ 8	6 ϕ 6	50 x 50	Eccentric e_x = 50.0 mm e_y = 00.0 mm
	GS1R2P3	200 x 200	300	4 ϕ 8	6 ϕ 6	50 x 50	Eccentric e_x = 50.0 mm e_y = 50.0 mm
	GS1R2P4	200 x 200	300	4 ϕ 8	6 ϕ 6	60 x 60	Concentric
	GS1R2P5	200 x 200	300	4 ϕ 8	6 ϕ 6	40 x 40	Concentric
	GS1R2P6	200 x 200	300	4 ϕ 8	6 ϕ 6	40 x 120	Concentric
	GS1R2P7	200 x 200	300	4 ϕ 8	6 ϕ 6	40 x 200	Concentric

Table 2. Details of tested high strength concrete blocks group (GS2).

Sub group	Block	Dimensions of cross-section mm x mm	Height mm	Longitudinal reinforcement	Lateral reinforcement	Size of loading plate mm x mm	Location of loading plate
GS2N	GS2NP1	200 x 200	400	---------	---------	50 x 50	Concentric
	GS2NP2	200 x 200	400	---------	---------	50 x 50	Eccentric e_x = 50.0 mm e_y = 00.0 mm
	GS2NP3	200 x 200	400	---------	---------	50 x 50	Eccentric e_x = 50.0 mm e_y = 50.0 mm
	GS2NP4	200 x 200	400	---------	---------	60 x 60	Concentric
	GS2NP5	200 x 200	400	---------	---------	40 x 40	Concentric
	GS2NP6	200 x 200	400	---------	---------	40 x 120	Concentric
	GS2NP7	200 x 200	400	---------	---------	40 x 200	Concentric
GS2R1	GS2R1P1	200 x 200	400	4 ϕ 8	5 ϕ 6	50 x 50	Concentric
	GS2R1P2	200 x 200	400	4 ϕ 8	5 ϕ 6	50 x 50	Eccentric e_x = 50.0 mm e_y = 00.0 mm
	GS2R1P3	200 x 200	400	4 ϕ 8	5 ϕ 6	50 x 50	Eccentric e_x = 50.0 mm e_y = 50.0 mm
	GS2R1P4	200 x 200	400	4 ϕ 8	5 ϕ 6	60 x 60	Concentric
	GS2R1P5	200 x 200	400	4 ϕ 8	5 ϕ 6	40 x 40	Concentric
	GS2R1P6	200 x 200	400	4 ϕ 8	5 ϕ 6	40 x 120	Concentric
	GS2R1P7	200 x 200	400	4 ϕ 8	5 ϕ 6	40 x 200	Concentric
GS2R2	GS2R2P1	200 x 200	400	4 ϕ 8	8 ϕ 6	50 x 50	Concentric
	GS2R2P2	200 x 200	400	4 ϕ 8	8 ϕ 6	50 x 50	Eccentric e_x = 50.0 mm e_y = 00.0 mm
	GS2R2P3	200 x 200	400	4 ϕ 8	8 ϕ 6	50 x 50	Eccentric e_x = 50.0 mm e_y = 50.0 mm
	GS2R2P4	200 x 200	400	4 ϕ 8	8 ϕ 6	60 x 60	Concentric
	GS2R2P5	200 x 200	400	4 ϕ 8	8 ϕ 6	40 x 40	Concentric
	GS2R2P6	200 x 200	400	4 ϕ 8	8 ϕ 6	40 x 120	Concentric
	GS2R2P7	200 x 200	400	4 ϕ 8	8 ϕ 6	40 x 200	Concentric

Table 3. Details of tested high strength concrete blocks group (GS3).

Sub group	Block	Dimensions of cross-section mm x mm	Height mm	Longitudinal reinforcement	Lateral reinforcement	Size of loading plate mm x mm	Location of loading plate
	GS3NP1	250 x 250	300	---------	---------	62.5 x 62.5	Concentric
	GS3NP2	250 x 250	300	---------	---------	62.5 x 62.5	Eccentric e_x = 62.5 mm e_y = 00.0 mm
GS3N	GS3NP3	250 x 250	300	---------	---------	62.5 x 62.5	Eccentric e_x = 62.5 mm e_y =62.5 mm
	GS3NP4	250 x 250	300	---------	---------	75 x 75	Concentric
	GS3NP5	250 x 250	300	---------	---------	50 x 50	Concentric
	GS3R1P1	250 x 250	300	4 ϕ 10	4 ϕ 8	62.5 x 62.5	Concentric
	GS3R1P2	250 x 250	300	4 ϕ 10	4 ϕ 8	62.5 x 62.5	Eccentric e_x = 62.5 mm e_y = 00.0 mm
GS3R1	GS3R1P3	250 x 250	300	4 ϕ 10	4 ϕ 8	62.5 x 62.5	Eccentric e_x = 62.5 mm e_y =62.5 mm
	GS3R1P4	250 x 250	300	4 ϕ 10	4 ϕ 8	75 x 75	Concentric
	GS3R1P5	250 x 250	300	4 ϕ 10	4 ϕ 8	50 x 50	Concentric
	GS3R2P1	250 x 250	300	4 ϕ 10	6 ϕ 8	62.5 x 62.5	Concentric
	GS3R2P2	250 x 250	300	4 ϕ 10	6 ϕ 8	62.5 x 62.5	Eccentric e_x = 62.5 mm e_y = 00.0 mm
GS3R2	GS3R2P3	250 x 250	300	4 ϕ 10	6 ϕ 8	62.5 x 62.5	Eccentric e_x = 62.5 mm e_y =62.5 mm
	GS3R2P4	250 x 250	300	4 ϕ 10	6 ϕ 8	75 x 75	Concentric
	GS3R2P5	250 x 250	300	4 ϕ 10	6 ϕ 8	50 x 50	Concentric

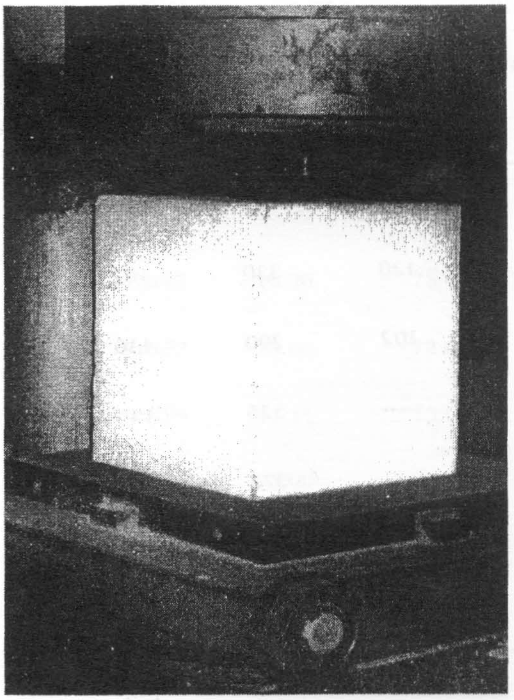

Fig. 4. Test setup.

2.3. Concrete mix

High strength concrete was used for all tested blocks. The cement used was locally produced commercially available ordinary portland cement, type I. Locally available natural desert sand was used as fine aggregate. The water cement ratio w/c was kept in the range of 0.28, pink lime stone with maximum aggregate size of 13 mm. was used as coarse aggregate. A commercially available super-plasticizer (water reducing agent) was used to increase workability.

3. Test results and discussions

The experimental results are presented in Tables 4. 5, and 6 for tested blocks in main groups GS1, GS2, and GS3, respectively. The ratio of total block area to loaded area, R', is given in the Tables for each block tested. The concrete cube compressive strength is presented for each sub group. Cracking and ultimate bearing strength are calculated for each block and are shown in the Tables. Finally, the non-dimensional ratio of ultimate bearing strength to concrete cube compressive strength, n, is calculated for each block tested and presented in the Tables. The cracking patterns after failure for tested blocks in main group GS1 are shown in Fig. 5.

3.1.Sub group GSIN

The seven blocks included in sub group GS1N are plain high strength concrete. For block GS1NP1, no cracks were detected until failure of the block takes place. The failure in this case was sudden, explosive, and was accompanied by a loud noise. Such explosive nature of failure was not reported in previous investigations on normal strength concrete blocks [5]. The crack pattern in this case consisted of one wide crack propagated from the top loaded surface downwards to the base of the block. At failure, the tensile stress at the top of the block exceeded the tensile strength of the concrete.

The ultimate bearing strength at failure was 170 N/mm^2. The non-dimensional ratio of ultimate bearing strength to concrete cube compressive strength n = 2.24 These values of ultimate bearing strength and the ratio n were presented by Ahmed et al. [5] as 132 N/mm^2 and 2.72 for normal strength concrete block having the same dimensions and loading configurations. Therefore, although the ultimate bearing strength of high strength concrete is greater than that for normal strength concrete, as expected, however the non-dimensional ratio n for high strength concrete is lower than that for normal strength concrete. Fig. 6 shows a comparison of the values of the ratio n for normal strength concrete blocks presented by Ahmed et al. [5] and those for high strength concrete blocks from the present study. It can be observed that the ratio n decreases in the case of high strength concrete compared to normal strength concrete blocks.

Figure 7 shows the effect of loading plate size in terms of the ratio of total area of block to loaded area, R', on the ratio n for all the nine sub groups considered. It should be noted that changing the size of bearing plate did not change the sudden explosive nature of failure. Also, no cracks were detected prior to failure for blocks GS1NP4 and GS1NP5.

Table 4. Experimental results for tested high strength concrete blocks group (GS1).

Sub group	Block	Ratio of total area to loaded area R'	Concrete cube compressive strength N/mm²	Cracking load kN	Cracking strength N/mm²	Bearing failure load kN	Ultimate bearing strength N/mm²	Ratio of ultimat bearing strength to concrete cube compressive strength, n
	GS1NP1	16.00	76.0	-----	-----	425	170	2.24
	GS1NP2	16.00	76.0	300	120	330	132	1.74
	GS1NP3	16.00	76.0	255	102	290	116	1.53
GS1N	GS1NP4	11.11	76.0	-----	-----	525	146	1.92
	GS1NP5	25.00	76.0	-----	-----	375	234	3.08
	GS1NP6	8.33	76.0	515	107	575	120	1.58
	GS1NP7	5.00	76.0	575	72	700	88	1.16
	GS1R1P1	16.00	73.5	-----	-----	475	190	2.59
	GS1R1P2	16.00	73.5	400	160	430	172	2.34
	GS1R1P3	16.00	73.5	300	120	380	152	2.07
GS1R1	GS1R1P4	11.11	73.5	-----	-----	600	167	2.27
	GS1R1P5	25.00	73.5	-----	-----	425	266	3.62
	GS1R1P6	8.33	73.5	550	115	690	144	1.96
	GS1R1P7	5.00	73.5	600	75	825	103	1.4
	GS1R2P1	16.00	75.0	-----	-----	500	200	2.67
	GS1R2P2	16.00	75.0	400	160	440	176	2.35
	GS1R2P3	16.00	75.0	310	124	400	160	2.13
S1R2	GS1R2P4	11.11	75.0	-----	-----	625	174	2.32
	GS1R2P5	25.00	75.0	-----	-----	450	281	3.75
	GS1R2P6	8.33	75.0	580	121	730	152	2.03
	GS1R2P7	5.00	75.0	610	76	850	106	1.41

Table 5. Experimental results for tested high strength concrete blocks group (GS2)

Sub group	Block	Ratio of total area to loaded area R'	Concrete cube compressive strength N/mm²	Cracking load kN	Cracking strength N/mm²	Bearing failure load kN	Ultimate bearing strength N/mm²	Ratio of ultimate bearing strength to concrete cube compressive strength, n
GS2N	GS2NP1	16.00	73.0	-----	-----	350	140	1.92
	GS2NP2	16.00	73.0	190	76	220	88	1.21
	GS2NP3	16.00	73.0	150	60	190	76	1.04
	GS2NP4	11.11	73.0	-----	-----	425	118	1.62
	GS2NP5	25.00	73.0	-----	-----	290	181	2.48
	GS2NP6	8.33	73.0	410	85	450	94	1.29
	GS2NP7	5.00	73.0	500	63	600	75	1.03
GS2R1	GS2R1P1	16.00	75.0	-----	-----	450	180	2.40
	GS2R1P2	16.00	75.0	310	124	380	152	2.03
	GS2R1P3	16.00	75.0	250	100	320	128	1.71
	GS2R1P4	11.11	75.0	-----	-----	525	146	1.95
	GS2R1P5	25.00	75.0	-----	-----	390	244	3.25
	GS2R1P6	8.33	75.0	500	104	615	128	1.71
	GS2R1P7	5.00	75.0	570	71	750	94	1.25
GS2R2	GS2R2P1	16.00	76.5	-----	-----	475	190	2.48
	GS2R2P2	16.00	76.5	320	128	400	160	2.09
	GS2R2P3	16.00	76.5	280	112	350	140	1.83
	GS2R2P4	11.11	76.5	-----	-----	575	160	2.09
	GS2R2P5	25.00	76.5	-----	-----	410	256	3.35
	GS2R2P6	8.33	76.5	510	106	640	133	1.74
	GS2R2P7	5.00	76.5	570	71	775	97	1.27

Table 6. Experimental results for tested high strength concrete blocks group (GS3).

Sub Group	Block	Ratio of total area to loaded area R'	Concrete cube compressive strength N/mm²	Cracking Load kN	Cracking Strength N/mm²	Bearing failure load (kN)	Ultimate bearing strength N/mm²	Ratio of ultimate bearing strength to concrete cube compressive strength, n
	GS3NP1	16.00	74.0	-----	-----	710	182	2.46
	GS3NP2	16.00	74.0	540	138	605	155	2.09
GS3N	GS3NP3	16.00	74.0	455	116	515	132	1.78
	GS3NP4	11.11	74.0	-----	-----	880	156	2.11
	GS3NP5	25.00	74.0	-----	-----	640	256	3.46
	GS3R1P1	16.00	74.0	-----	-----	805	206	2.78
	GS3R1P2	16.00	74.0	575	147	715	183	2.47
GS3R1	GS3R1P3	16.00	74.0	530	136	645	165	2.23
	GS3R1P4	11.11	74.0	-----	-----	990	176	2.38
	GS3R1P5	25.00	74.0	-----	-----	730	292	3.95
	GS3R2P1	16.00	76.0	-----	-----	840	215	2.83
	GS3R2P2	16.00	76.0	635	163	750	192	2.53
GS3R2	GS3R2P3	16.00	76.0	565	145	670	172	2.26
	GS3R2P4	11.11	76.0	-----	-----	1025	182	2.39
	GS3R2P5	25.00	76.0	-----	-----	755	302	3.97

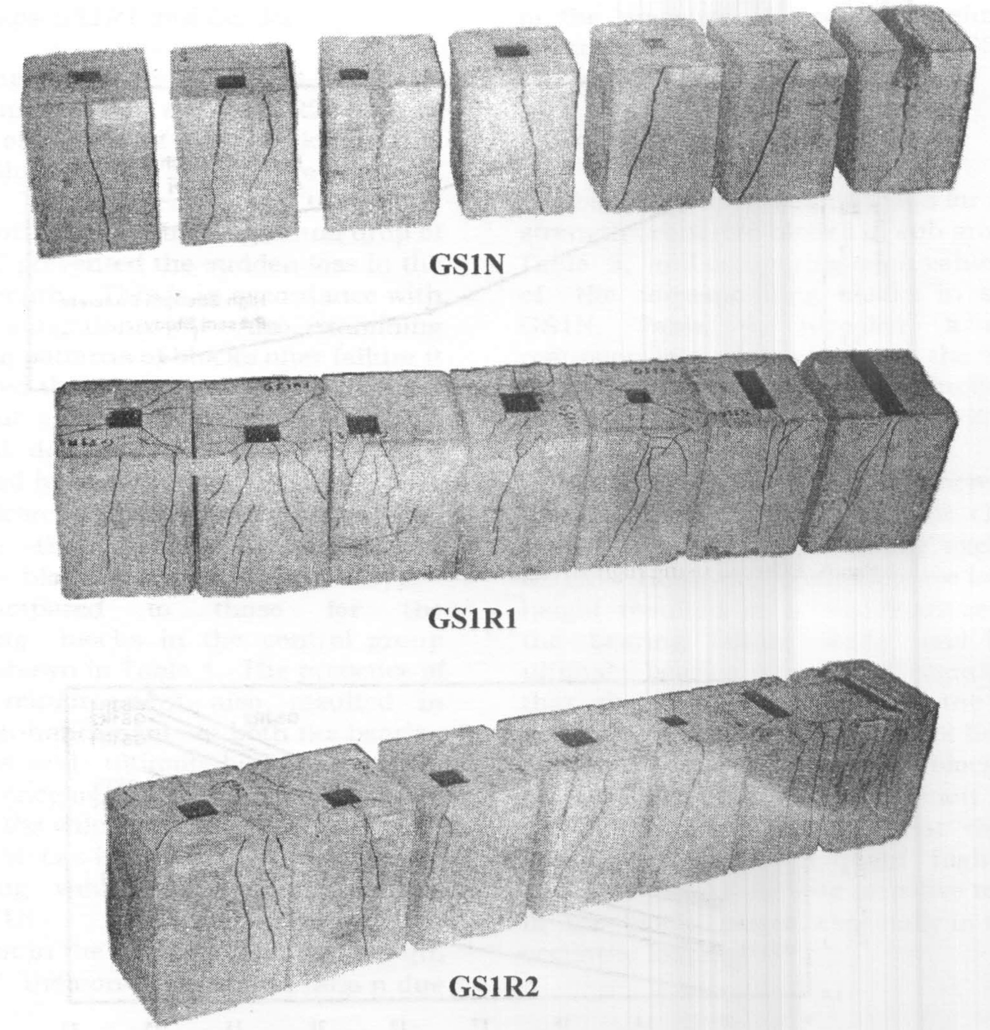

Fig. 5. Cracking patterns for tested high strength concrete blocks in main group GS1.

The eccentricity of the bearing plate resulted in a significant decrease in the bearing failure load and hence the ultimate bearing strength. In this case the non-dimensional ratio n decreased to 1.74 and 1.53 for blocks loaded eccentrically in one direction and two directions, respectively compared to 2.24 in the case of concentric load, block GS1NP1. Such decrease in the ratio n represents about 22% and 32% for blocks GS1NP2 and GS1NP3, respectively. Fig. 8 shows the effect of the eccentricity of loading plate on the ultimate bearing strength in terms of the non-dimensional ratio, n, for all the nine sub groups considered.

Blocks loaded under rectangular and strip loading plates, GS1NP6 and GS1NP7, also failed in an explosive sudden mode of failure accompanied by a loud noise. In the case of strip loading pattern a concrete wedge pushed into the block. A split crack formed dividing the block into two segments. It should be noted that the non dimensional ratio n decreased significantly in the case of rectangular and strip loading patterns compared to that in the case of concentric square loading pattern.

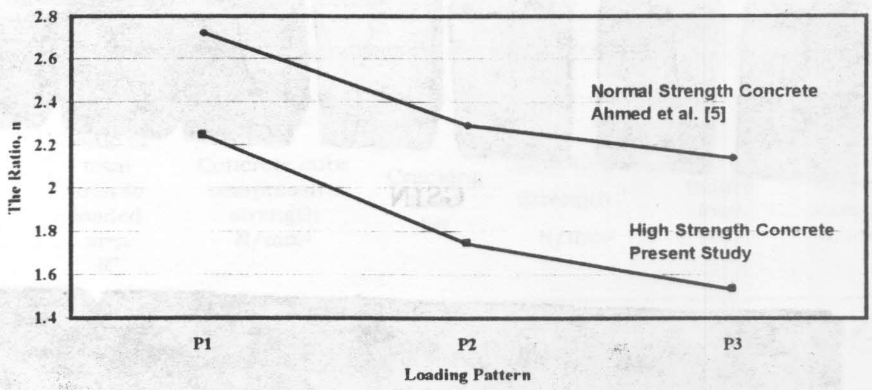

Fig. 6. Effect of using high strength concrete on the non-dimensional ratio, n.

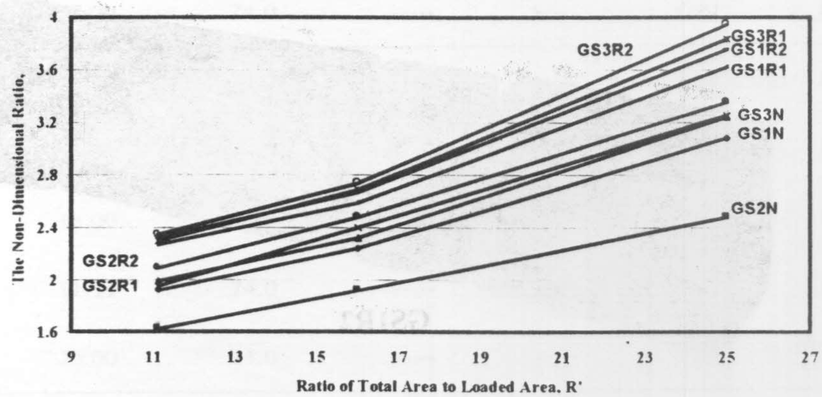

Fig. 7. Effect of loading plate size on the Ultimate bearing strength.

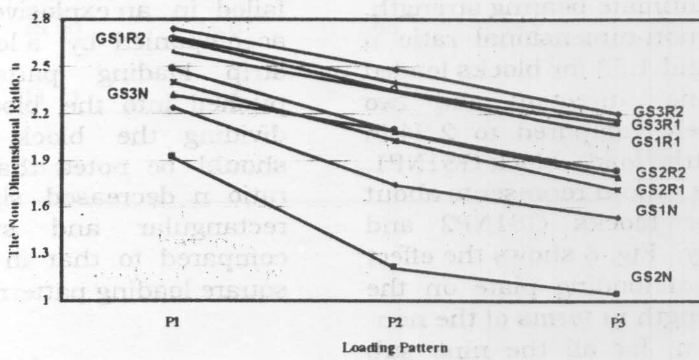

Fig. 8. Effect of Eccentricity of Loading Plate on the Ultimate Bearing Strength.

3.2. Sub groups GS1R1 and GS1R2

The inclusion of reinforcement for blocks in sub groups GS1R1 and GS1R2 changed the nature of failure of the blocks. In this case the failure of the blocks were relatively ductile. The presence of transverse reinforcement resulted in a gradual drop of the load and prevented the sudden loss in the bearing strength. This is in accordance with previous investigations [6]. Also, examining the cracking patterns of blocks after failure it was observed that the presence of transverse reinforcement controlled the width of cracks. A significant decrease in the width of cracks were observed in this case.

A significant increase in the cracking load and hence the cracking strength was observed for blocks in sub group GS1R1, ρ_t = 2.26%, compared to those for the corresponding blocks in the control group GS1N, as shown in Table 4. The presence of transverse reinforcement also resulted in significant enhancement in both the bearing failure loads and ultimate bearing strength. Such enhancement may be detected comparing the values of the non dimensional ratio, n, for blocks in sub group GS1R1 to the corresponding values in the control sub group GS1N. Fig. 9 presents the enhancement in the ultimate bearing strength in terms of the non-dimensional ratio n due to the presence of transverse reinforcement for tested blocks in main group GS1, for the seven loading patterns considered.

3.3. Sub group GS2N

Observing the cracking loads for plain high strength concrete blocks in sub group GS2N, Table 5, and comparing such values to those of the corresponding blocks in sub group GS1N, Table 4, revealed a significant reduction in such loads due to the increase in the blocks height. Such reduction in the cracking load ranged between 13% and 41%, depending on the loading pattern.

It should be noted that the increase in the blocks height, GS2N, did not change the nature of failure previously explained for GS1N. However, such increase in the block height resulted in a significant reduction in the bearing failure loads and hence the ultimate bearing strength. It should be noted that the greatest reductions in the ratio n, as a result of increasing the block height, were observed in the case of blocks loaded eccentrically in one direction and two directions This indicates that the ultimate bearing strength of plain high strength concrete blocks is very sensitive to a change in the block height, especially in the case of eccentric loading.

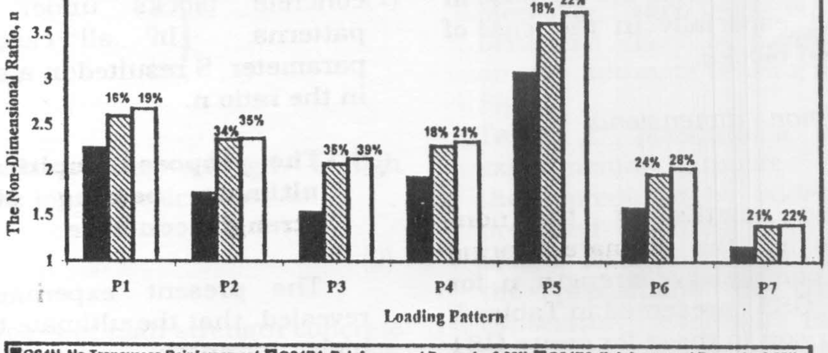

Fig. 9. The enhancement in the ultimate bearing strength due to the presence of transverse reinforcement.

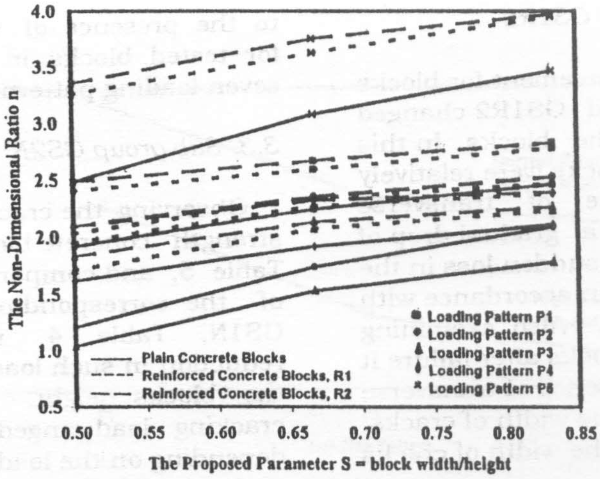

Fig. 10. Relationship between the proposed parameter, S, and the non-dimensional ratio n.

3.4. Sub groups GS2R1 and GS2R2

Similar observations were found for reinforced high strength concrete blocks in sub groups GS2R1 and GS2R2. However, examining the percentage of reduction in the bearing strength, in terms of the non dimensional ratio n, resulting from the increase in the blocks height it can be observed that the inclusion of transverse reinforcement in high strength concrete blocks reduces the sensitivity of the ultimate bearing strength of the blocks to a change in the block height. It should be also noted that the effectiveness of the inclusion of transverse reinforcement increases with the increase in the blocks height, especially in the case of eccentrically loaded blocks.

3.5. The proposed non - dimensional parameter, S.

Examining the results of the non-dimensional ratio of the ultimate bearing strength to cube compressive strength, n, for groups GS2 and GS3 presented in Tables 5 and 6, in comparison to those for group GS1 presented in Table 4, it was observed that: (i) increasing the block height in main group GS2 resulted in a significant decrease in the ratio n; and, (ii) increasing the block cross section size in main group GS3 resulted in a significant increase in the ratio n.

Bearing in mind that increasing the block height, main group GS2, decreased the ratio of block width to block height to 0.5 compared to 0.667 in the case of main group GS1. Also, increasing the block cross-section size, main group GS3, increased the block width to block height ratio to 0.833. Therefore, it is suggested herein that the effects of both the block height and the cross-section size be combined together in terms of a non-dimensional parameter S = block width/block height. Figure 10 demonstrates the relationship between the proposed parameter S and the non-dimensional ratio n for plain and reinforced high strength concrete blocks under different loading patterns. In all cases increasing the parameter S resulted in a significant increase in the ratio n.

4. The proposed empirical formula for the ultimate bearing strength of high strength concrete

The present experimental investigation revealed that the ultimate bearing strength of high strength concrete is of coarse significantly higher than that for normal strength concrete. However, it was found that the non-dimensional ratio of ultimate bearing strength to cube compressive strength n for high strength concrete was significantly lower than that in the case of normal strength concrete as shown in Fig. 6. Also, it was found that the non-dimensional ratio n depends on a number of independent significant variables namely: (1) The non-dimensional ratio R' = total area of concrete/loaded area; (2) the proposed non-dimensional parameter S = concrete width/height; (3) transverse reinforcement percent ρ_t in percent; and, (4) the eccentricities of load in both directions expressed in terms of non-dimensional ratios e_x/b and e_y/b. The prediction of the mean of the dependent variable n can be improved using a multiple regression analysis. The multiple regression method establishes the effect of each independent variable with the other independent variables kept constant, Kennedy and Neville [9].

Based on the results obtained from the experimental study conducted herein an empirical formula was developed for the estimation of the non-dimensional ratio n = ultimate bearing strength/concrete cube compressive strength for high strength concrete, using a multiple regression analysis. The details of the analysis is presented in Kennedy and Neville [9]. Once the ratio n is calculated using the proposed empirical formula and multiplying the concrete cube compressive strength, f_{cu}, by such calculated ratio yields the ultimate bearing strength of concrete, f_{bu}. The proposed formula is in the form of:

$$n = \frac{0.47 \times R'^{0.63} \times S^{0.43} \times \left(1+\rho_t\right)^{0.15}}{\left(1 + \frac{e_x}{b} + \frac{e_y}{b}\right)^{0.82}} . \quad (1)$$

Then the ultimate bearing strength of high strength concrete may be calculated as:

$$f_{bu} = n \times f_{cu} . \quad (2)$$

It should be noted that high strength concrete is defined by the ACI 318 [3] as concrete with cylinder compressive strength greater than 40 MPa (f_{cu} = 50 MPa). High strength concrete used in practice with a concrete cube compressive strength ranging between 50 MPa and 100 MPa. An average value of f_{cu} was chosen for the current investigation ranging between 73 and 76.5 MPa. Therefore, the current presented proposed empirical formula will be limited to such range of concrete cube compressive strength. However, it is recommended that future research be directed towards the study of the ultimate bearing strength of high strength concrete in order to cover the wide range of concrete cube compressive strength (50 to 100 MPa).

4.1. Comparison of experimental results to those predicted by current codes of practice and the proposed empirical formula

Codes of practice (ECP-98 [2], ACI 318-95 [3], and DIN 1045 [10]) present equations for the estimation of the ultimate bearing strength of concrete. However, such code equations were originally developed and calibrated using results from testing normal strength concrete specimens. The current experimental investigation revealed that the non-dimensional ratio of ultimate bearing strength to concrete cube compressive strength n for high strength concrete is significantly lower than that in the case of normal strength concrete, Fig. 6. Furthermore, these code equations do not take into account the effect of several significant factors on the ultimate bearing strength of concrete such as the effect of the ratio of block width to block height, Fig. 10. Moreover, such code equations neglect the beneficial effect of transverse reinforcement on the ultimate bearing strength of concrete, Fig. 9.

Table 7 presents a comparison of the experimental ultimate bearing strength to those predicted by codes of practice and the proposed empirical formula for some of the blocks tested. The comparison revealed that the predictions of code equations are conservative especially in the case of blocks having transverse reinforcement. Also, it can be observed that the code predictions become more conservative when increasing the ratio R' of total area to loaded area (blocks GS1NP5, GS1R1P5, and GS1R2P5). It can be also observed that the predictions of the proposed empirical formula correspond well with the experimental results with a difference not exceeding 6%.

It is concluded herein that although the predictions of the equations presented by different codes of practice are conservative, however such equations can be used safely for the estimation of the ultimate bearing strength of high strength concrete. The experimental results presented in this paper and the proposed empirical formula may be beneficial when updating different codes of practice.

Table 7 Comparison of experimental results to those predicted by codes of practice and the proposed empirical formula.

Block	Experimental ultimate bearing strength $f_{bu(exp)}$ N/mm²	Theoretical ultimate bearing strength $f_{bu(th)}$ N/mm²				$f_{bu(th)}/f_{bu(exp)}$			
		ECP-98 [2]	ACI 318-95 [3]	DIN 1045-88 [10]	Proposed empirical formula	ECP-98 [2]	ACI 318-95 [3]	DIN 1045-88 [10]	Proposed empirical formula
GS1NP1	170	101.9	103.4	106.4	171.8	0.60	0.61	0.63	1.01
GS1NP4	146	101.9	103.4	106.4	136.8	0.70	0.71	0.73	0.94
GS1NP5	234	101.9	103.4	106.4	228.0	0.44	0.44	0.45	0.97
GS1R1P1	190	101.9	103.4	106.4	198.5	0.54	0.54	0.56	1.04
GS1R1P4	167	101.9	103.4	106.4	158.0	0.61	0.62	0.64	0.95
GS1R1P5	266	101.9	103.4	106.4	264.6	0.38	0.39	0.40	0.99
GS1R2P1	200	101.9	103.4	106.4	204.5	0.51	0.52	0.53	1.02
GS1R2P4	174	101.9	103.4	106.4	171.0	0.59	0.59	0.61	0.98
GS1R2P5	281	101.9	103.4	106.4	284.3	0.36	0.37	0.38	1.01

ECP-98 [2]: $f_{bu} = 0.67\, f_{cu} \sqrt{\frac{A_2}{A_1}}.\quad \sqrt{\frac{A_2}{A_1}} \le 2$

ACI 318-95 [3] $f_{bu} = 0.85\, f'_c \sqrt{\frac{A_2}{A_1}}.\quad \sqrt{\frac{A_2}{A_1}} \le 2$

DIN 1045-88 [10] $f_{bu} = \frac{\beta_R}{2.1} \sqrt{\frac{A}{A_1}}.\quad \le 1.4\, \beta_R$

5. Summary and conclusions

The previous investigations found in the literature do not cover all the important aspects of the problem of bearing. Most of these investigations have concentrated on concentrically loaded plain concrete specimens. Also. most of these investigations have considered small size specimens. No research efforts were directed towards the study of the bearing strength of high strength concrete. An extensive experimental study was conducted in this paper including 57 plain and reinforced high strength concrete specimens. all having the shape of blocks subjected to concentric and eccentric square. rectangular. and strip loadings. The objective of the experimental study was to investigate the bearing strength of high strength concrete. The effect of several significant factors on the ultimate bearing strength of high strength concrete was detected. Furthermore. the experimental data obtained was used to develop an empirical formula for the estimation of the ultimate bearing strength of high strength concrete. The formula takes into account all the important factors affecting the ultimate bearing strength of concrete. Finally. the experimental results for the ultimate bearing strength of some of the blocks tested were compared to those predicated by codes of practice and the proposed empirical formula. Based on this study, the following conclusions can be drawn:

1- The behavior of high strength concrete in bearing is significantly different than that of normal strength concrete. The bearing failure mode in the case of plain high strength concrete is sudden explosive and accompanied by a loud noise. The ultimate bearing strength of high strength concrete is greater than that for normal strength concrete, as expected. However, the non-dimensional ratio of ultimate bearing strength to concrete cube compressive strength for high strength concrete is significantly lower than that in the case of normal strength concrete.

2- The inclusion of transverse reinforcement in high strength concrete blocks changed the nature of bearing failure from an explosive sudden failure to a relatively ductile failure and prevented the sudden drop in the bearing strength. Moreover, the inclusion of transverse reinforcement controlled the width of cracks of concrete at failure.
3- The inclusion of transverse reinforcement in high strength concrete blocks significantly increases the cracking loads and hence the cracking strength. Also, the presence of such reinforcement enhances the bearing failure loads and hence the ultimate bearing strength.
4- Increasing the blocks height causes a significant reduction in the ultimate bearing strength of concrete. However, the inclusion of transverse reinforcement in high strength concrete blocks reduces the sensitivity of the ultimate bearing strength of concrete to a change in the block height. Furthermore, the effectiveness of the inclusion of transverse reinforcement increases with the increase in the block height, especially in the case of eccentrically loaded blocks.
5- Increasing the block cross-section size increases the cracking strength and the ultimate bearing strength for both plain and reinforced high strength concrete blocks.
6- The effects of both the block height and the cross-section size can be combined together in terms of a non-dimensional parameter (=block width/height). An increase in such proposed parameter significantly increases the ratio of ultimate bearing strength to concrete cube compressive strength.
7- The equations presented by different codes of practice for the estimation of the ultimate bearing strength of concrete were originally developed and calibrated using results from testing normal strength concrete specimens. The non-dimensional ratio of ultimate bearing strength to concrete cube compressive strength for high strength concrete is significantly lower than that for normal strength concrete. In addition, such code equations neglect the effect of several important factors on the ultimate bearing strength of concrete. The predictions of these equations are conservative. However, such equations can be used safely for the estimation of the ultimate bearing strength of high strength concrete.

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Notations

b	is the width of concrete block.
e_x	is the eccentricity of load in x-direction.
e_y	is the eccentricity of load in y-direction.
f_{bu}	is the ultimate bearing strength of concrete.
f_{cu}	is the concrete cube compressive strength.
h	is the height of concrete block.
n	is the non-dimensional ratio of ultimate bearing strength of concrete to cube compressive strength.
R'	is the ratio of loaded area of concrete to total area.
S	is the proposed non-dimensional parameter (=block width/height).
ρ_t	is the transverse reinforcement percent.

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