Effect of Concrete Compressive Strength and Compression Reinforcement in Compression Zone on the Ductility of Reinforced Concrete Beams

Dr. Sawsan Akram Hassan
Engineering College, University of Al-Mustansiriyah/ Bagdad.
Email:Sawsanakram@yahoo.com
Awadh Ewayed Ajeel
Engineering College, University of Al-Mustansiriyah/ Bagdad.

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Abstract

Ductility is a mechanical property used to describe the extent to which materials can be deformed plastically without fracture giving warning of impending failure. In this paper the effect of increasing the strength in the compression zone of reinforced concrete beams on ductility was investigated. Seven reinforced concrete beams were tested for this purpose. The tested beams were divided into two groups depending on the manner at which the strength of the compression zone was increased. In the first group, the increase was done by increasing the amount of compression reinforcement. Four ratios of compression reinforcement were adopted. In the second group, the increase in the strength of the compression zone was done by increasing the concrete compressive strength in the upper third of the cross section which was subjected to compression stresses. Four compressive strengths were adopted .One beam was used as reference for the two groups. It was found that, the compression zone strengthening, by the two manners, increases both strength and ductility of the beams; but the increases due to increase the ratio of compressive reinforcement is higher and more safety than that attained due to increasing concrete compressive strength.

Keywords: Ductility, compressive strength, compression steel ratio, compression zone.

تأثير مقاومة انضغاط الخرسانة والتسليح في منطقة الضغط على مطيلية العتبات الخرسانية المسلحة

الخلاصة

المطيلية هي خاصية ميكانيكية تستخدم لوصف المدى الذي يمكن للمواد التشوه اللدن بدون انكسار معطية تحذير من الفشل الوشيك.يتناول البحث الحالي تأثير زيادة مقاومة منطقة الضغط للعتبات الخرسانية المسلحة على مطيليتها. تم فحص سبع عتبات خرسانية مسلحة لهذا الغرض، قسمت العتبات الخرسانية الى مجموعتين اعتماداً على الطريقة التي تم بها زيادة مقاومة منطقة الضغط. في المجموعة الأولى؛ حصلت زيادة في كمية قضبان حديد تسليح الضغط باستخدام أربع نسب من تسليح الضغط. أما في المجموعة الثانية؛ فحصلت الزيادة في مقاومة منطقة الضغط بزيادة مقاومة انضغاط الثلث العلوي للعتبة واستخدمت اربعة قيم لمقاومة

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2412-0758/University of Technology-Iraq, Baghdad, Iraq
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الانضغاط للخرسانة. استخدمت عتبة مرجعية واحدة في كلا المجموعتين. بينت النتائج أن تقوية منطقة الضغط، بكلا الطريقتين، قد عززت مقاومة ومطيلية العتبات المفحوصة. ولكن التعزيزات التي استحصلت بزيادة تسليح الانضغاط كانت أعلى وأكثر أماناً بالمقارنة مع تلك المستحصلة بزيادة مقاومة الخرسانة للانضغاط.

INTRODUCTION

Ductility is a desirable structural property because it allows stress redistribution and provides warning of impending failure; therefore, it is a structural design requirement in most design codes. In reinforced concrete (RC) structures, ductility is defined as the ratio of post yield deformation to yield deformation which it usually comes from steel [1- 4].

When beams are under-reinforced by design, that failure is initiated by yielding of the steel reinforcement, followed, after considerable deformation at no substantial loss of load carrying capacity, by concrete crushing and ultimate failure. This mode of failure is ductile and is guaranteed by designing the tensile reinforcement ratio to be substantially below (ACI 318 requires at least 25% below) the balanced ratio, which is the ratio at which steel yielding and concrete crushing occur simultaneously. The reinforcement ratio thus provides a metric for ductility, and the ductility corresponding to the maximum allowable steel reinforcement ratio provides a measure of the minimum acceptable ductility [2, 3].

On the other hand, conventional RC beams reinforced with ductile bars have ductility problems when the failure is caused by the compressive crushing of concrete in which the tensile reinforcement does not yield. This occurs in over-reinforced case (usually not permitted by most design codes) in which, ductility and deformability of the structure are significantly reduced [4].

Ductility of structures is important to ensure large deformation and give sufficient warning while maintaining an adequate load-carrying capacity before a structural failure so that a total collapse may be prevented and lives saved. Ductility is also the basis of modern structural design approaches (for example, moment redistribution). In seismic structures or structures subjected to impact loading such as bridge beams, ductility becomes an extremely important consideration [4- 9].

Objective

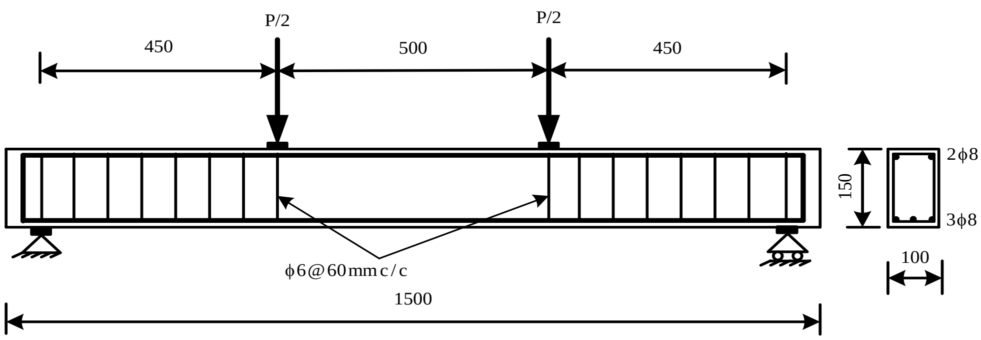
The ductility and methods of increasing ductility is one of the most active areas in the study of concrete structures. In present work, experimental study is adopted to investigate the effect of strengthening the compression zone on the ductility of RC beams. The compression zone is strengthened by two corresponding ways; the first is increasing the compression steel area whilst the second is increasing its compressive strength. Each increment in compression steel area (in a beam) corresponds an increment in compressive strength of the compression zone (in other beam) to maintain a same carrying capacity for the two beams. The purpose is to select the best option of them in the ductility and deformability of the RC beams.

Experimental Program

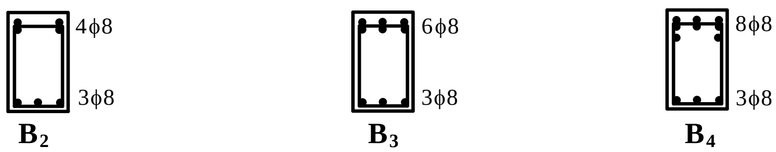
The experimental program of the present work consists of casting and testing of seven reinforced concrete beams of size of 100x150x1500mm and three cubic control units of 150mm size for each beam to obtain the concrete compressive strength. The beams were tested under two concentrated loads. The distance between the two point loads was 500 mm c/c. All beams have the same flexural and shear reinforcement. The beams were divided into two groups; each group consists of three beams in addition to control beam. The concrete compressive strengths and reinforcement rates for all the beams are shown in Table (1) and Figure (1) to study the effect of the intended parameters on the ductility of these beams.

Table (1): Details of the tested beams

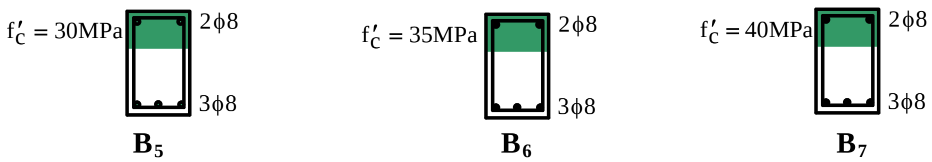
Group	Beam Symbol	Compressive Strength (f'_c) MPa		Flexural Reinforcement		Shear Reinfo-rcement c/c
		Upper Third	Lower Two Thirds	Tension (ρ)	Compr-ession (ρ')	
Control Beam	B_1	25	25	3Ø8mm	2Ø8mm	Ø6mm @60mm
Group A	B_2	25			4Ø8mm	
	B_3	25			6Ø8mm	
	B_4	25			8Ø8mm	
Group B	B_5	30			2Ø8mm	
	B_6	35			2Ø8mm	
	B_7	40			2Ø8mm	



a. Control beam B_1



b. Group A



c. Group B

Figure (1): Details of the tested beams (all dimensions in mm).

Materials

1.Cement, Corse Aggregate and Fine Aggregate

Ordinary Portland cement type I was used [10]. Crushed coarse aggregate of a 14 mm maximum size was used. Natural river sand, zone 2, with a 2.71 fineness modulus was used as fine aggregate according to IQS: 45 1984 [11].

2.Reinforcing Steel

Deformed steel bars of (8mm) and (6 mm) nominal diameters were used; Table (2) shows the mechanical properties of reinforcing bars.

Table (2):Properties of reinforcing bars

Nominal Diameter mm	Measured Diameter mm	Area (A_s) mm^2	Yield Stress (f_y) MPa	Ultimate Stress (f_u) MPa	Elongation %
8	7.77	47.42	423.7	601.8	18.3
6	5.67	25.25	383.1	545.3	19.6

3.Superplasticizer (SP)

Chloride free liquid admixture commercially named TopBond 603 complies with ASTM C 469–86 [12] was used. Properties and description of the used superplasticizar are shown in Table (3).

Table (3): Properties and description of superplasticizer

Appearance	Specific Gravity	Chloride Content	Flash Point
Dark Brown Liquid	1.21 at 25±2°C	Free	Unexpected

Mix Proportion

Four mixes were used in the present work; **Table (4)** shows the details of the used mixes

Table (4): Details of the used mixes

Mix No.	Nominal Strength MPa	Tested Strength (f'_c) MPa	Cement kg/m^3	Sand kg/m^3	Gravel kg/m^3	Water L/m^3	SP	Belong to Beam
1	25	27.6	385	575	1150	192	-	All Beams
2	30	31.3	430	605	1125	130	6.5	B5
3	35	37.2	475	575	1100	144	7.2	B6
4	40	42.4	520	575	1142	150	7.5	B7

Molding, Casting and Curing

Wood molds were used to cast all beams. The molds were lubricated before fixing the reinforcing bars inside it. Then the concrete was mixed for about three minutes by using a horizontal rotary mixer of 0.19 m^3 capacity and then poured into three layers; each of which was compacted by a vibrating table. Three 150mm cubic specimens were cast as control units with each beam to investigate the compressive strength of its concrete. The beams with two concrete compressive strength were achieved lower two third of beam section, then after initial setting was happened, the upper third was cast. The specimens and the control units were covered with nylon to prevent water evaporation for 24 hours. After that, the molds were stripped and the cast specimens were submerged in water containers in the laboratory for 28 days to be cured. After curing the specimens were brought out of water.

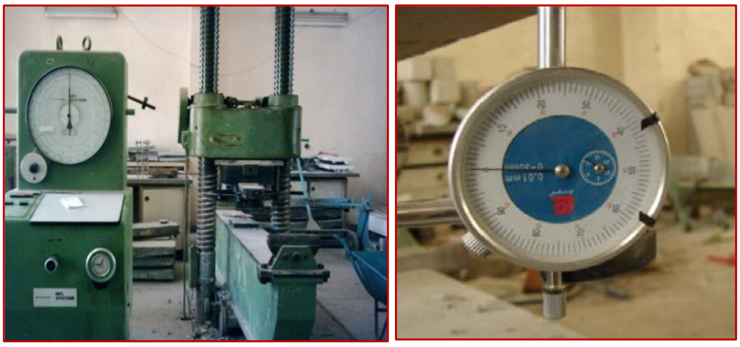
Tests Setup and Instrumentation

Load Measurements

The beams were tested by a universal testing machine of 3000 kN maximum capacity Figure (2.a).

Deflection Measurements

One mechanical dial gauge of 0.01mm accuracy Figure (2.b) was used to measure the midspan deflection at the center of the tested beams during testing procedure.



a. Universal testing machine **b. Mechanical dial gauge**

Figure (2): Dial gauge and testing machine

Testing Procedure

The beams were painted by white color to facilitate detection of cracks firstly. The candidate beam for test was positioned and supported in the testing machine and prepared by fixing the positions of supports and load points. After that, the dial gauge was positioned at the center of the bottom face of the beam. Each beam was loaded directly at the top face with two equal concentrated loads. Loading started with an increment of 2 kN and continued up to failure. At each stage of load increment, midspan deflection was recorded.

Results and Discussion

The results of the present work were listed in Table (5). The cracking load (P_{cr}), ultimate (failure) load (P_u) and the length of the crashing zone at the top face of the beam (where compression zone is given). Also, deflection at ultimate load (Δ_u) which reflects the maximum deflection at the center of tested beam was listed in the table to explain the aims of the present study.

Table (5): Results of the tested beams

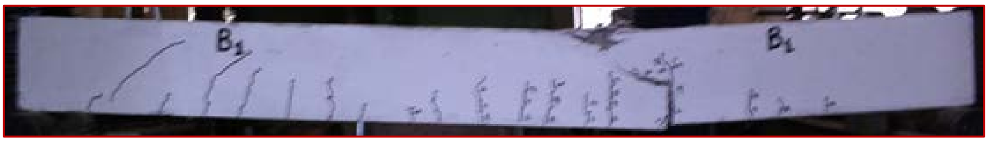
Group	Beam Symbol	P_{cr} kN	P_u kN	Δ_u mm	Crashing Zone mm
Control Beam	B_1	4	25	10.43	125
Group A	B_2	4	32	13.93	190
	B_3	4	33	17.38	440
	B_4	4	41	28.83	440
Group B	B_5	4	28	12.48	80
	B_6	4	31	13.84	80
	B_7	4	35	17.71	70

Cracking Load (P_{cr})

The cracking load (P_{cr}) was the same (4kN) for all tested beams; this means the lack of way of compression zone strengthening on cracks appearance. However, that way of strengthening takes a considerable part on cracking pattern of the beam. So, the number of cracks in the group A beams (increment of ρ') is greater than group B beams (increment of f'_c).

The orientation of crack leads to conclude that all the beams were safe against shear failure. On other wise, spalling concrete was clear in the tension zones of beams B_4, B_6 and B_7 besides ripping of the concrete clear cover; and this spalling concrete in tension zone increases with more compression zone strengthening generally and especially with increasing the concrete compressive strength, so that this palling appears in two beam of group B (B_6 and B_7) in comparison with single beam in group A (B_4).

The failure mechanism of the entire tested beams was yielding of tension steel bar and developing crack numbers and height followed by crushing the concrete in the top of compression zone. The extension of the crushing zone of group A was greater than that of the control beam $B_1$and in increase with ρ' while the crushing zone of group B was smaller than that of the control beam and in decrease with $f'_c$and that is clear in Figure (3).



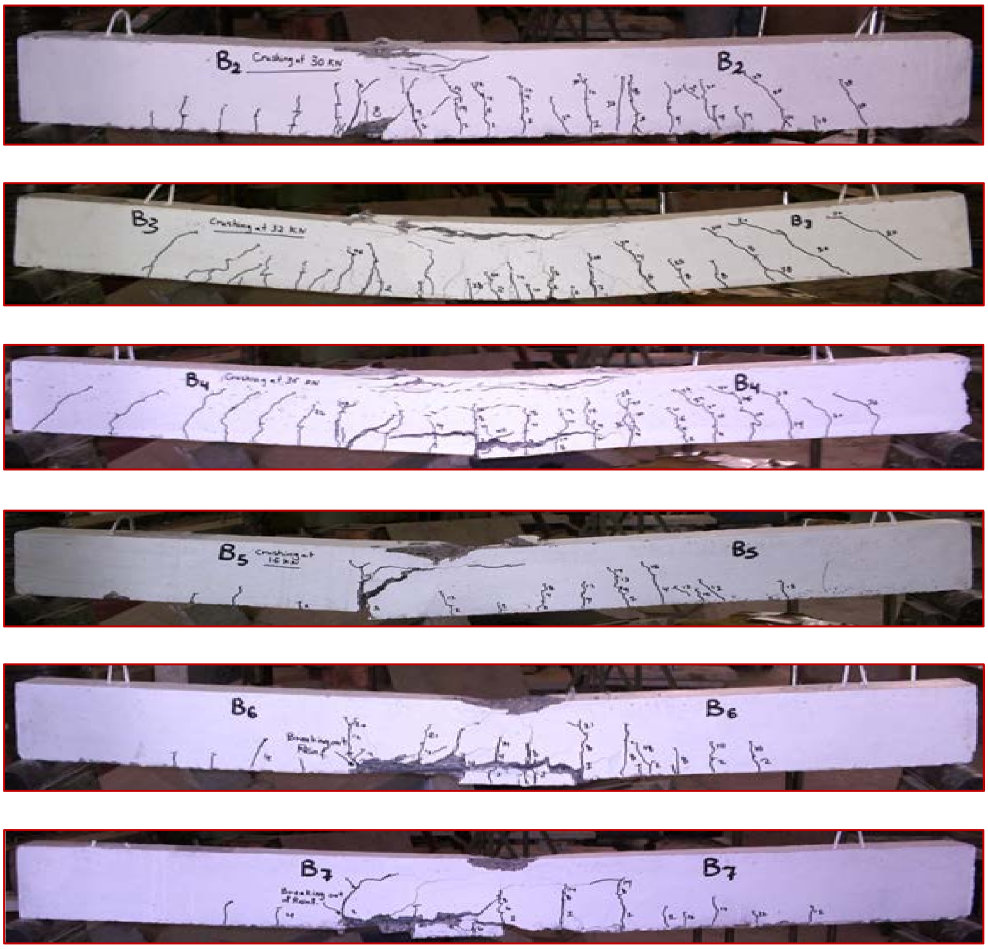


Figure (3): Cracking Patterns of the tested beams

Ultimate Load (P_u)

The ultimate load (P_u) of all tested beams of the two groups was increased; that revealed the effect of increasing the strength of the compression zone on enhancing the ultimate strength of the beam, as shown in Table (6).

Enhancement amount in the two groups of beams varies with the way of compression zone strengthening; focusing on group A reveals that the increase values of ultimate strength were 28, 32 and 64% which is not in the same rate of enhancement in comparison with monotonic rate of increasing the compression steel ratio (ρ')and this result can be confirmed by group B beams where increase values of ultimate strength were 12, 24 and 40% which is not in the same rate with increasing the compressive strength(f_c').

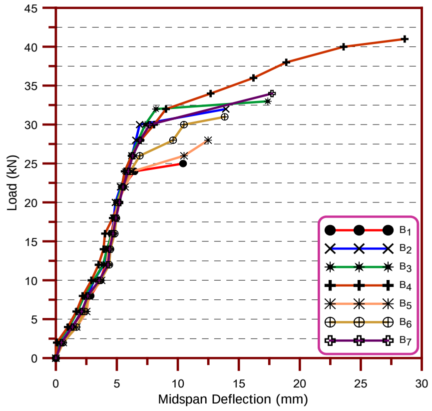
Table (6) also revealed that; the increase of ρ'achieves enhancing in the beam ultimate strength more than enhancement can be achieved by increasing f_c' in the compression zone.

Table (6): Increasing the ultimate strength of the tested beams

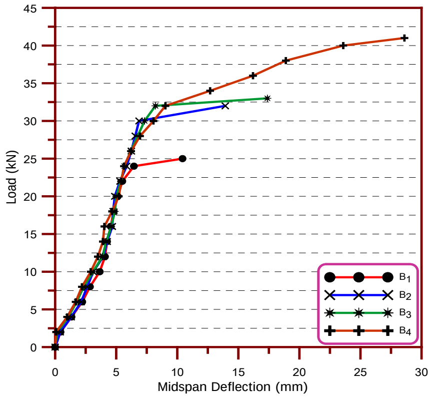
Group	Beam Symbol	P_u kN	P_u Increase %	Δ_y mm	Δ_u mm	μ_d Δ_u/Δ_y	μ_d Increase %
Control Beam	B_1	25	-	6.45	10.43	1.62	-
Group A	B_2	32	28	6.87	13.93	2.03	25.31
	B_3	33	32	8.21	17.38	2.17	33.95
	B_4	41	64	9.03	28.83	3.19	96.91
Group B	B_5	28	12	6.29	12.48	1.98	22.22
	B_6	31	24	6.88	13.84	2.01	24.07
	B_7	34	40	7.69	17.71	2.30	41.98

Ductility

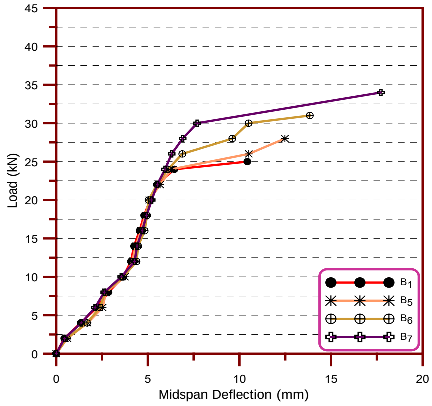
The ductility index (μ_d), as listed in Table (6), was calculated depending on (Δ_u/Δ_y), where the deflection at ultimate load (Δ_u) is the last recorded value just before beam failure and (Δ_y) is the deflection at tension reinforcing steel at yield which was observed from the experimental load-deflection curves, Figure (4), when the curve appearance transformed from linear part to inelastic.



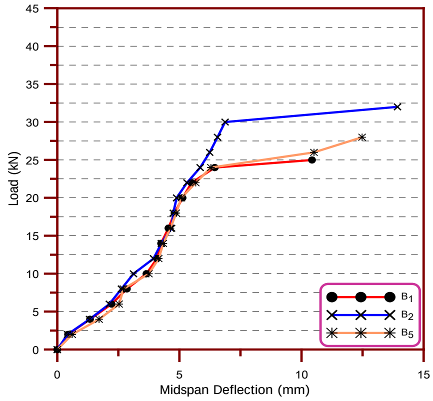
a. All beams



b. Group A + B_1

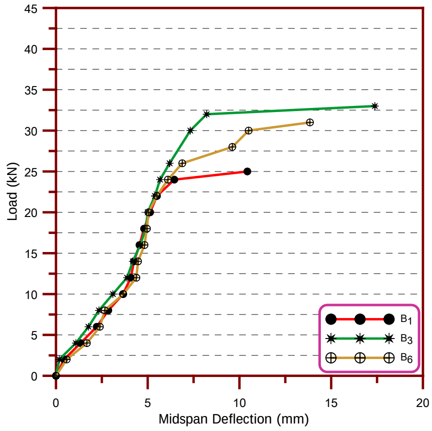


c. Group B + B_1

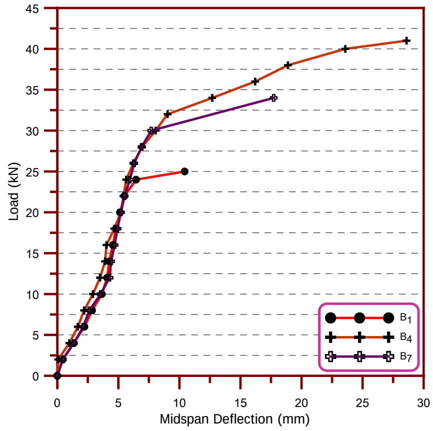


d. B_1 + B_2+B_5

Figure (4) To be continued



e. B_1 + B_3 +B_6



f. B_1 + B_4 +B_7

Figure (4): Comparison among load-deflection curves of the test beams

Figures (4.a-c) show the similar behavior of all tested beams, with slight reduction in deflection from beam to another before the yield points. The reduction in the deflection value occur with increase the beam strength, therefore; B_4 exhibits the smallest deflection, however after the yield point the value of deflection begins to increase obviously according to the concerned load and lead to magnify the ductility of the beam. In spite of the ductility increase in the two groups A and B beams but group A achieved the greatest value; thereby, the ductility index of B_4 was 3.19 which is approximately the doubled of B_1 index which was 1.62, while the higher ductility index in group B was 2.3 achieved by B_7. On the same wise, for every two corresponding beam from groups A and B, the comparison revealed that the ductility of group A is higher than group B ones, and that confirmed from Figures (4.d-f).It is concluded remark, the compression zone strengthening by increasing (ρ') lead to improve the deflection and ductility properties of RC beams better than the strengthening by increasing(f_c').

Another comparison among ductility and ultimate load increases was accomplished to investigate the safe way of attainable strengthening for the load carrying capacity, as shown in Figure (5). For the two groups of beams, it can be noticed that the increase in ductility is convergent to the increase in ultimate load, except B_4 (with highest ρ') which exhibits a considerable ductility increase against the ultimate load increase, that means continuity in increasing ρ' may be lead to improve the ductility higher than a good increase in ultimate load (ductility increase per ultimate strength increase is approximately equals 1.5). On the other hand, increasing f'_c in the compression zone can be improved the ductility and the ultimate strength of the RC beam but not in the same rate to that improving comes due to increasing ρ' from a side and there is no rising in ductility against the ultimate strength from another side. Therefore, increasing ρ' enhances the ductility against the ultimate load better than increasing f'_c of the compression zone. So that, the increase of compression steel rate is the more safety technique for strengthening the RC beams.

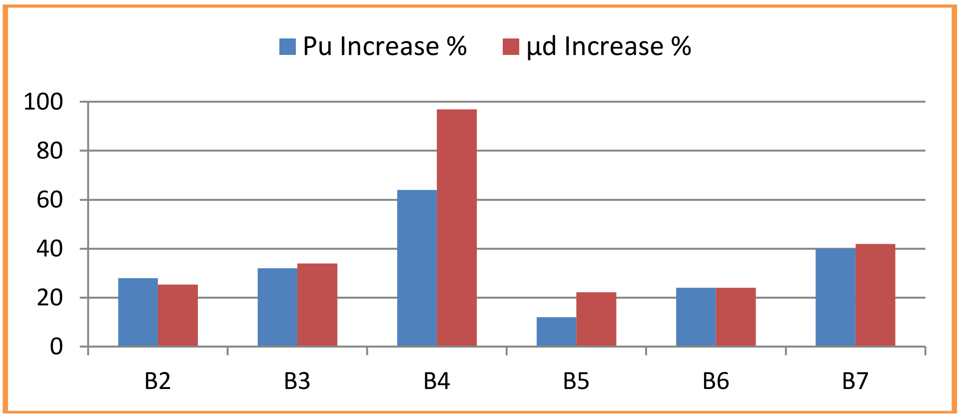


Figure (5): Comparison between ductility and ultimate load of the test beams

CONCLUSIONS

1. Strengthening the compression zone of RC beam improves its behavior, through increasing its ultimate load and ductility with slight reduction in deflection values.
2. Strengthening the compression zone of RC beam by increasing its compressive strength leads to improve the ultimate strength and ductility approximately in the same rate. However, this rate of improvement stills less than a corresponding improvement rate achieved by increasing the compression steel ratio.
3. Increasing the compression steel rate is preferable for improving the ductility than the ultimate strength, besides that, raising the compression steel rate of RC beam means enhancing both ductility and ultimate strength.
4. Considerable ductility increase in high compressive steel RC beam make this technique of strengthening safety and accomplish with more cracked and crushed concrete to give a further indication before failure.

Notation

A_s: Area of reinforcing steel bars (mm^2).
f'_c: Compressive strength of concrete (MPa).
f_y: Yield stress of reinforcing steel bars (MPa).

f_u: Ultimate strength of reinforcing steel bars(MPa).
P: Applied load (kN).
P_{cr}: Cracking load (kN).
P_u: Ultimate load (kN).
Δ_y: Deflection at yield load of tension reinforcing bars (mm).
Δ_u: Deflection at ultimate load (mm)
ρ: Ratio of tension reinforcement.
ρ': Ratio of compression reinforcement.
$\emptyset$: Diameter of reinforcing steel bars (mm).
μ_d: Ductility index (Δ_u/Δ_y).

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