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The effect of concrete strength and reinforcement on toughness of reinforced concrete beams

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Abstract

The objective pursued with this work includes the evaluating of the strength and the total energy absorption capacity (toughness) of reinforced concrete beams using different amounts of steel-bar reinforcement. The experimental campaign deals with the evaluation of the threshold load prior collapse, ultimate load and deformation, as well as the beam total energy absorption capacity, using a three point bending test. The beam half span displacement was measured using a displacement transducer, and the applied force was monitored using a load cell. The tested samples consists on a set of ten reinforced concrete beams having three different levels of steel-bar-reinforcement percentages and four different concrete compositions (i.e., giving rise to a different values of concrete strength). It was observed that the most influential parameter in the beams energy absorption capacity is the amount of steel-bar reinforcement. The results have presented good agreement between themselves. In fact, for beams with a given concrete compressive strength, a decrease in beam's deformation was measured for higher steel-bar-reinforcement percentages. Moreover, the results had shown that for a particular steel-bar-reinforcement percentage, the concrete compressive strength have also influence in the total energy absorption capacity of the beams.

Keywords: High performance concrete; Concrete strength; Steel-bar-reinforcement; Beam toughness

1. Introduction

Significant progress in mechanical and durability performance of concrete has been achieved through a combination of new chemical admixtures and mineral additions during the last decade, leading to production of High Performance Concrete (HPC). Enormous advantages arise from the utilisation of such (HPC) in structures where demands on strength, durability and real service life are high [1]. Examples of such constructions are long span bridges, structures in marine environment and offshore structures [2].

However, the progress does not always bring only advantages. In fact, it is observed that concrete become more brittle and less deformable as its compressive strength increases. This behaviour has become evident from experimental tests carried out on HPC specimens subjected to axial compression. In such tests the occurrence of an extremely explosive rupture is noted. This brittle behaviour of HPC has raised concerns with regards to its real application. In fact, the observed decrease on deformability of HPC need not necessarily result in a deformability decrease of reinforced concrete structural elements, because a reinforced concrete element combines a brittle HPC with high toughness reinforced bars.

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2. Previous studies

Concrete consists of the cement paste that acts as the matrix linking the aggregates. The matrix is porous and usually filled with fluid. Other constituents present are additives and admixtures in order to impart specific properties of the fresh concrete such as higher plasticity, retardation or acceleration of setting time.

The application of fracture mechanics to concrete involves precautions and the success in its applicability is still investigated. The first experimental study on the applicability of fracture mechanics to concrete was carried out by Kaplan [3] in 1961. Other studies had been followed and nowadays a continuous investigation in this domain is considered of priority [4,5] as it can contribute to production of concrete with increased strength. Moreover, Leslie et al. [6] have studied the influence of the concrete strength and the steel-bar-reinforcement percentage parameters on toughness of HPC reinforced beams submitted to a pure bending moment. Subsequent studies, carried out by Tognon et al. [7], Pastor et al. [8], Shin et al. [9], Ahmad et al. [10] and Lopes et al. [11] have confirmed the influence of the parameters prior enunciated although the results are still scarce and are not completely concordant concerning toughness dependence with those parameters. Hence, there is a need for further research in order to evaluate the effect of concrete strength and steel-bar-reinforcement percentage on the total energy absorption capacity of concrete beams. In this research work a conventional concrete (45 MPa compressive strength) and a HPC (90 and 150 MPa compressive strength) were manufactured and the steel-bar-reinforcement percentage area varied from 0.428 to 1.684 which lie between 0.066 and 8.11 which are the allowable minimum and maximum values indicated by Portuguese building code for specimens using 45 MPa concrete strength.

3. Experimental work

3.1. Concrete mixes tested

Three different concrete compositions were selected in order to achieve three different classes of concrete strength, namely B45, B90 and B150. The specimens were labelled with a prefix *B* that means *beam* and the number denotes the concrete strength in MPa. Moreover, a mixture similar to B90 was used with partial replacement of sand by ground rubber particles, labelled as BB60. The rubber addition to the concrete had the purpose to study the influence of rubber on both concrete strength and deformability.

Cement type II – 42.5 was used in production of concretes B45 and B90 along with river sand and crushed granite coarse aggregate with dimensions between *1 and 10 mm*. The water reducing agent Rheobuild 1000 was also used. For B150 cement type I – 52.5 R, metakaolin and superplastizer type Glénium C313 were used. The different concrete compositions are summarized in Table 1.

Fig. 1 shows a Scanning Electron Microscopy (SEM) top view micrograph [12] for B45 conventional concrete. It is clearly shown the sand and crushed granite coarse aggregate surrounded by the cement past and the presence of large pores in the concrete mass is also evident.

In order to evaluate the strength of concrete, three concrete cubes ($5 \times 5 \times 5\ cm^3$) were moulded (see Fig. 2(a)). The strength of mixes was obtained, at the same age as the beam, using a hydraulic press (see Fig. 2(b)).

Table 1
Concrete compositions

Materials	B45	B90	B150	BB60
Cement (kg/m^3)	300	360	600	360
W/C ratio	0.45	0.4	0.28	0.4
Sand (kg/m^3)	1197	1011.4	–	767.33
Coarse aggregates (kg/m^3)	712.5	776.3	–	776.3
Metakaolin (kg/m^3)	–	40	90	40
Super plasticizer (l/m^3)	6	7.2	75	7.2
Rubber (kg/m^3)		–	–	76.73
Crushed ceramic (kg/m^3)	–	–	1385	–

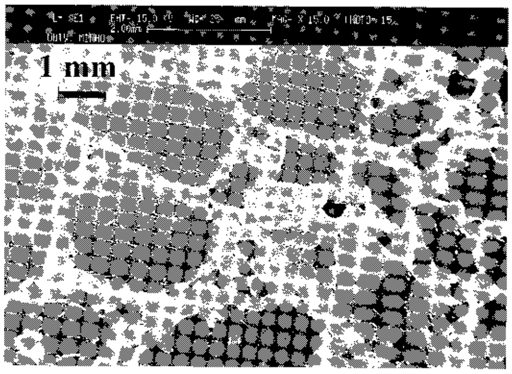

Fig. 1. SEM micrograph showing the surface of the conventional concrete specimen.

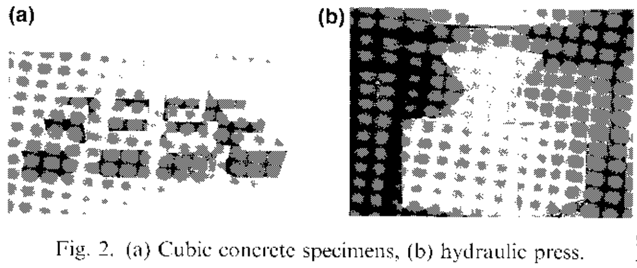

Fig. 2. (a) Cubic concrete specimens, (b) hydraulic press.

3.2. Reinforced concrete beams

In the experimental campaign a set of destructive tests were performed on ten reinforced concrete beams. The beams were cast in the horizontal position using a wood formwork. The casting of the beams was carried out with the reinforcement steel bars properly embedded in the fresh concrete. After 50 days the beams were removed from the mould, transported to the working testing area and positioned on the testing steel frame. The beams, simply supported, were submitted to the action of a point force applied on the beams central region. In Fig. 3 are represented schematically the beams and the reinforcement bar configurations.

Table 2 presents the characteristics of each beam: the total area of the steel-bars A_s, the steel-bar percentage area (as per cent of beam cross-section area) ρ, and the density of concrete μ. Furthermore, it is noted that all beams have square cross-section ($h \times b = 100\ \mathrm{cm}^2$) and the depth of the tension steel from the top surface of the beam cross-section (i.e., the effective height) is $d = 9$ cm. The beams were grouped in four series as a function of the concrete strength.

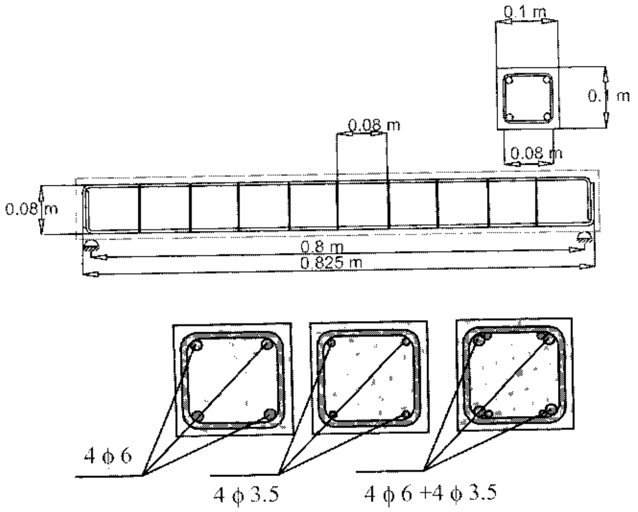

Fig. 3. Beam geometry and detail for the reinforcement bar configurations.

Table 2
Summary of experimental design

Series	Group code	A_s (cm^2)	ρ (%)	μ (kg/m^3)
1	1B45-0.428	0.3848	0.428	
	1B45-1.256	1.131	1.256	2280
	1B45-1.684	1.516	1.684	
2	2B90-0.428	0.3848	0.428	
	2B90-1.256	1.131	1.256	2420
	2B90-1.684	1.516	1.684	
3	3B150-0.428	0.3848	0.428	
	3B159-1.256	1.131	1.256	2155
	3B150-1.684	1.516	1.684	
4	*4BB60-1.256*	1.131	1.256	*2340*

Each beam group is labelled by its series, where the first number after the letter B is the concrete compressive strength *fc*, and the last number is the percentage area of the reinforcement steel-bar. The fourth series (4BB60-1.256) refers to a beam with rubber addition to the concrete. Fig. 4 shows schematically a beam on its experimental set-up as well as the instrumentation used for the measurement of the results.

3.3. Concrete compressive strength

The concrete strength was evaluated by compression tests on specimens cured for 50 days. Fig. 5(a)–(c) shows the results of compression tests performed on cubic concrete specimens. Fig. 5(d) refers to the cubic specimen of concrete with rubber addition. The three curves represented in each figure correspond to three experimental tests performed for each concrete mixture. The peak value registered is taken as the strength of the specimen.

Results from concrete B90 and B150 indicate a brittle fracture (explosive rupture in the case of B150) with a sharp loss of strength after the peak value. In the case of the concrete B45 specimen, results indicate a higher toughness showing some strength after reaching the peak value. Indeed, given that the composition of the BB60 concrete is similar to that of the B90 concrete, it is noted that the addition of rubber causes a loss of strength (some 30%), but the loss of strength when peak value is reached is less abrupt.

3.4. Bending strength of the reinforced concrete beams

3.4.1. Experimental results

Fig. 6(a)–(d) presents the load displacement curves, i.e., behaviour curves, obtained from the experimental measurements of beams submitted to a three point bending test. Each graph refers to a series of three tested beams (corresponding to each concrete strength values) with increasing levels of the steel-bar reinforcement

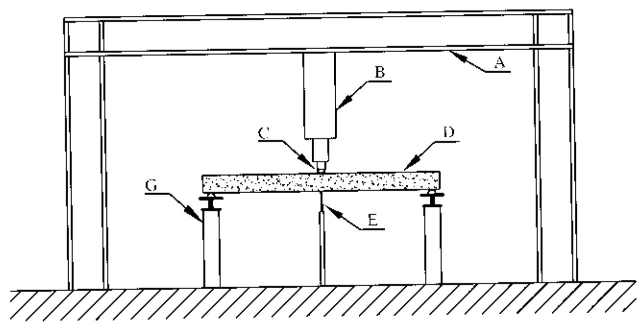

Fig. 4. Three-point loading experimental set-up: (A) steel frame structure, (B) hydraulic actuator, (C) load cell, (D) beam, (E) displacement transducer, (G) metallic support.

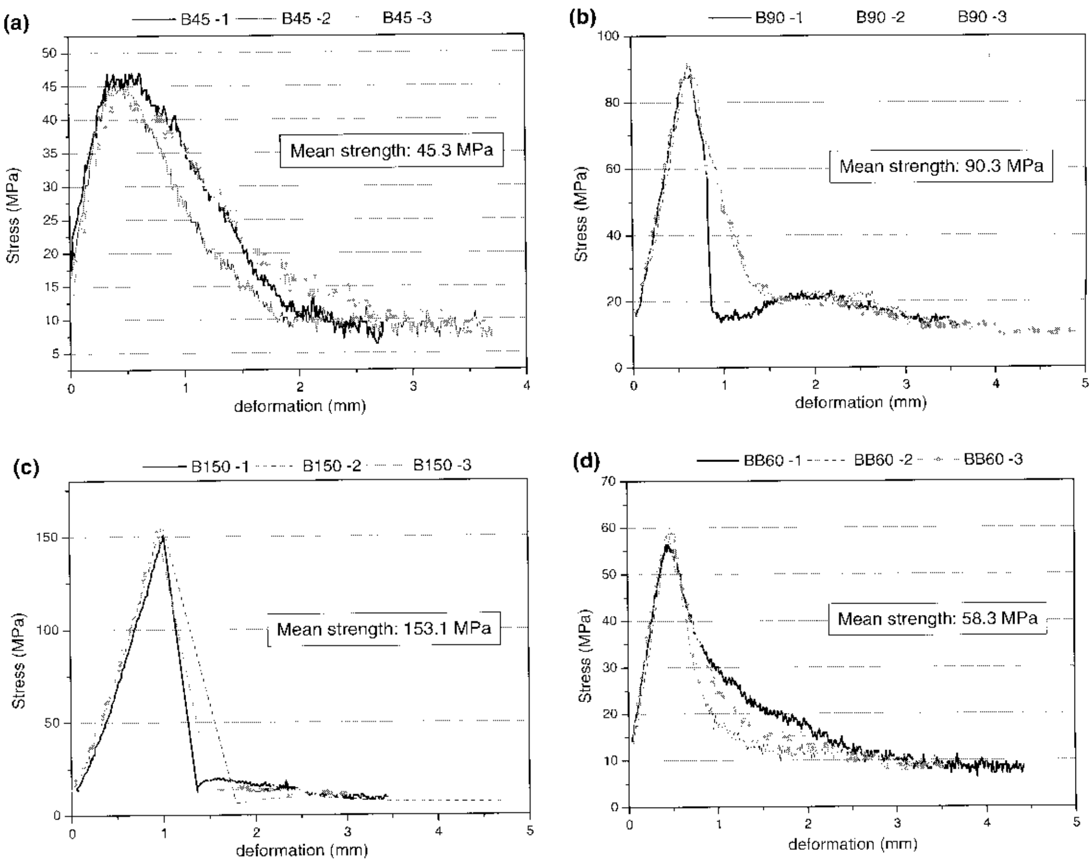

Fig. 5. Experimental results from compressive tests performed on cubic concrete test-specimens: (a) B45 specimen, (b) B90 specimen, (c) B150 specimen, (d) BB60 specimen.

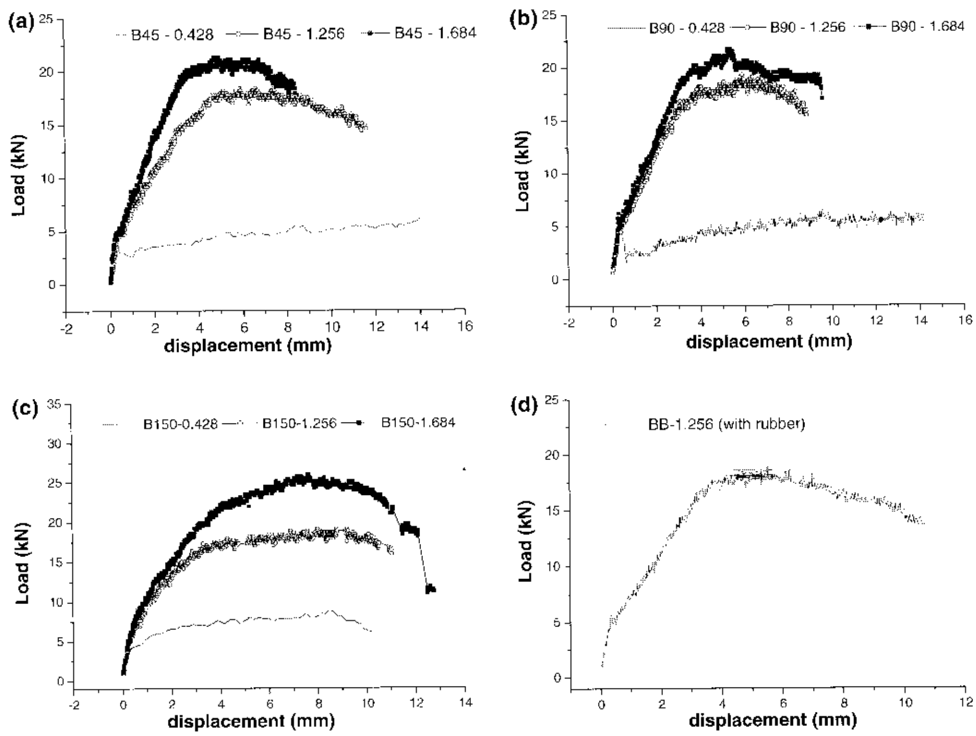

Fig. 6. Experimental beam *load displacement* curves for different concrete strength values and steel-bar-reinforcement percentage: (a) B45 specimen, (b) B90 specimen, (c) B150 specimen, (d) BB60 specimen.

percentage. For all series it can be observed that for increased levels of the steel-bar reinforcement, the beam maximum load is also increased. However, in all situations, the beam deflection measured at the maximum load (i.e., the beam mid span peak displacement δ_m) decreases for higher levels of steel-bar reinforcement. In fact, this is a normal consequence of the revised moment of inertia, $I_{cracked\ effective}$: the more steel the higher $I_{cracked\ effective}$ and the lower the deflection. Concerning the curve last points, i.e., the last measured load (P_u) and beam last deflection (δ_u) it is observed that for the particular 1.684 steel-bar reinforcement percentage, higher concrete strength values leads to an increase of the last beam deflection and a decrease of the last measured load (see Table 3). In this case, the higher concrete strength the lower $I_{cracked\ effective}$ and the higher the last deflection.

Fig. 7(a) shows the experimental set-up with a beam being tested while Fig. 7(b) shows the rupture cross-section located at the beam mid span.

4. Toughness

4.1. Evaluating toughness of beam series

The toughness of a material (U_T) is defined as the capacity of a material to absorb energy in the plastic domain up to rupture [13]. This parameter is difficult to evaluate, but a process to determine the toughness of a material consists of taking the total area A limited below the stress–strain curve or the force–deformation curve, divided by the volume of the tested sample. This area gives an insight of the amount of energy per unit volume that the material can support up to rupture. In the scope of this work it was used as beam rupture criterion, the last measured applied load (P_u) at which an abrupt load decrease occurred (last points in Fig. 6) which coincided with the physical collapse of the beam such as seen in Fig. 7(b). The total energy A was determined for the tested beams by two different procedures: (i) first determining the best polynomial equation representing the experimental data, then performing an integration to compute the area under the force–displacement curve, (ii) measuring the area under force–displacement curve. It was observed that both procedures produced very similar results (difference lower than 1%).

In order to analyze the influence of the concrete strength on the beam toughness, it was necessary to group the beams with equal steel-bar reinforcement percentage, ρ. Table 3 groups the beams according to ρ and shows the experimental results from the behaviour curves as well as the determined toughness values, U_T.

Fig. 8 presents for each ρ, the beams toughness evolution as a function of the concrete compression strength. The observed tendencies show that for a particular steel-bar reinforcement percentage, toughness increases reasonably when concrete strength increases from 90 to 150 MPa.

In general, the observed tendency can be explained by the following mechanism: for a particular steel-bar reinforcement percentage the depth of the neutral axis decreases for higher concrete strength values. This behaviour gives rise to an increase of the last beam deflection (because the revised moment of inertia $I_{cracked\ effective}$ will decrease) leading to a beam toughness

Table 3
Last parameters and beam toughness

Beam	ρ (%)	P_u (kN)	δ_u (mm)	U_T (MPa)
1B45	0.428	6.3	14	0.00885
2B90		5.0	14.2	0.00833
3B150		6.1	10.2	0.00906
1B45	1.256	14.6	11.6	0.02114
2B90		15.9	8.9	0.01643
3B150		15.9	11.1	0.02272
4BB60		13.9	10.7	0.01951
1B45	1.684	17.9	8.4	0.0239
2B90		17.0	9.5	0.0232
3B150		11.2	12.8	0.0322

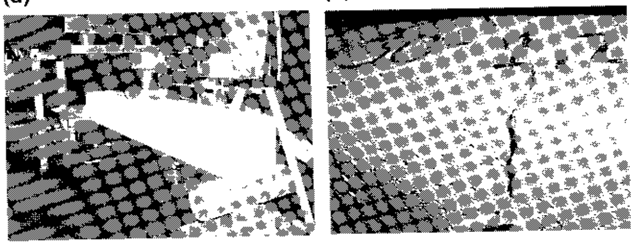

Fig. 7. (a) Experimental set-up for bending test. (b) Mid span cracked cross-section.

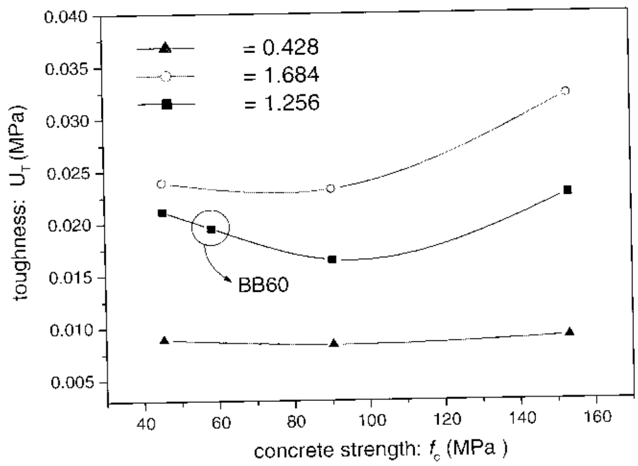

Fig. 8. Influence of concrete strength and steel-bar-reinforcement percentage on beam's toughness.

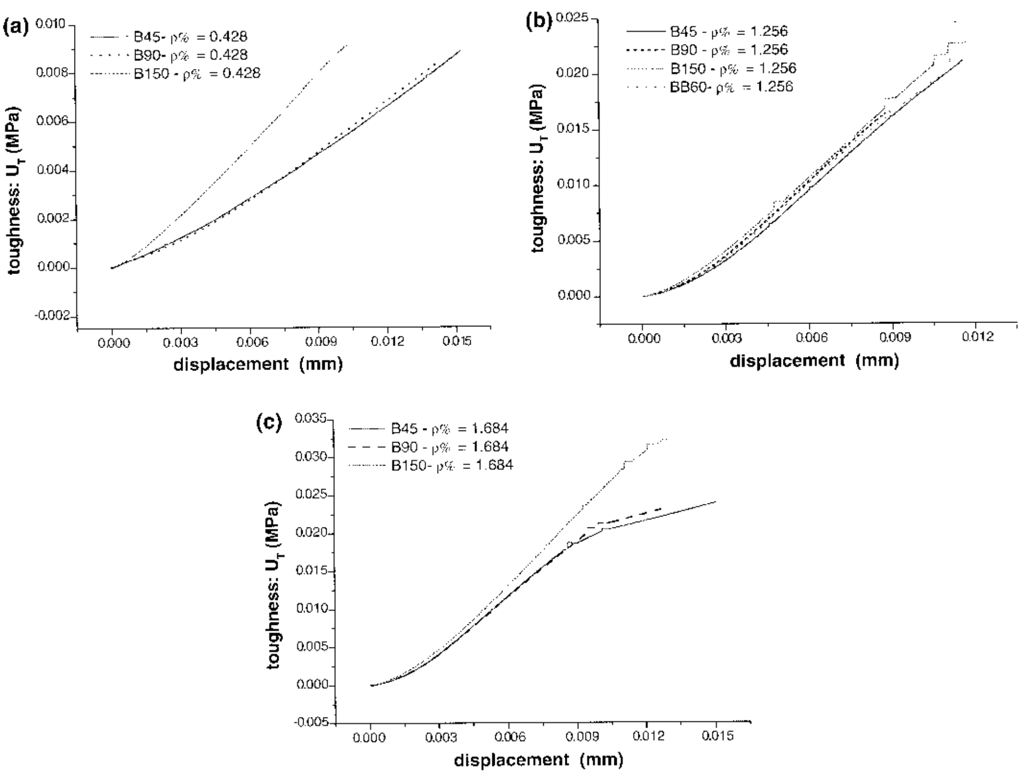

Fig. 9. Toughness as a function of the beam mid span displacement: (a) $\rho = 0.428$, (b) $\rho = 1.256$, (c) $\rho = 1.684$.

increase. Thus, a decrease of the depth of the neutral axis appears to compensate and surpass the loss of concrete toughness for higher concrete strengths. In practice this behaviour indicates that a combination of a high performance concrete with high steel-bar-reinforcement percentage can reduce the brittle behaviour of the structure.

Fig. 9(a)–(c) shows the toughness evolution as a function of the beam mid span displacement. The same global tendency is observed showing that the better performance is achieved by the association of high performance concrete with high steel-bar-reinforcement percentage. Moreover, Fig. 9 also shows that toughness–displacement curves have a parabolic shape for small values of beam deformation, which is indicative of an elastic behaviour. Meantime, for the higher deformation regime, but sufficiently far from the last points, the curves present almost a constant slope meaning a plastic behaviour of the tested element.

4.2. The effect of steel-bar reinforcement percentage on beam deformation

Fig. 6 shows that for a particular concrete strength, the beam mid span peak displacement (δ_m) decreases for higher levels of steel-bar reinforcement. This behaviour can be explained as follows: due to an increase on the steel-bar-reinforcement percentage the depth of the neutral axis increases and as a consequence, the revised moment of inertia $I_{\text{cracked effective}}$ will increase leading to a concomitant decrease of the beam deflection. Fig. 10 plots the δ_m as a function of ρ.

For increased levels of steel-bar reinforcement percentage it can be observed that for the particular case of 45 and 90 MPa concrete strength, δ_m decreases strongly up to $\rho \cong 1.25\%$ and levelling off thereafter. However, for a 150 MPa concrete strength the beam

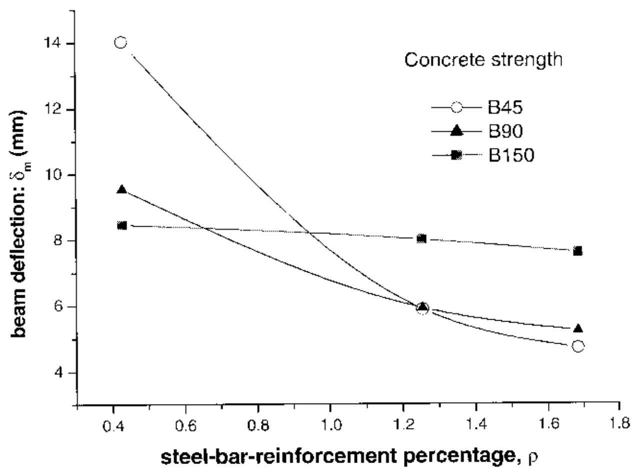

Fig. 10. Beam mid span peak displacement, δ_m as a function of steel-bar-reinforcement percentage.

deflection remains almost constant for all levels of steel-bar reinforcement percentage.

The experimental results can be summarized as follows:

1. HPC and high steel-bar reinforcement percentage: B150 – 1.684 compared with conventional concrete with the equivalent steel-bar reinforcement: B45 – 1.684
   - The bending peak load is increased in 22%.
   - The beam mid span peak displacement is increased in 58%.
   - The beam last displacement is increased in 52.3%.
   - The beam bending toughness is increased in 35%.
   - Reduces in 5.5% the concrete density.
2. HPC with addition of rubber particles as partial replacement of sand (results of BB60 compared with B90 for = 1.256%)
   - Reduces in 33% the concrete strength.
   - The bending last load is decreased in 12.6%.
   - The beam last displacement is increased in 17%.
   - The beam bending toughness is increased in 16%.
   - Reduces in 3.3% the concrete mass density.

5. Conclusions

In this research work it was observed that the most influential parameter in the toughness of the reinforced concrete beams is the steel-bar-reinforcement percentage. The experimental results show a good agreement between themselves indicating that in general, for constant values of concrete strength the more steel-bar reinforcement the lower the beam mid span peak displacements. This is a consequence of the increase of the revised moment of inertia due to the increase of the depth of the beam neutral axis. Experimental results also show that for a particular steel-bar-reinforcement percentage the concrete strength influences reasonably the beams energy absorption capacity (toughness): the higher the concrete strength the higher the beam toughness. This behaviour is more pronounced for the high performance concrete B150.

Interesting practical applications may be emphasized to concrete with partial replacement of sand by rubber particles. Indeed, due to lower density it can be used in buildings as an indoor structural material, separation panels with high damping capacity to vibrations or eventually in situations where a large deformation capacity required.

Based on experimental results it is reasonable to assume that the association of a high performance concrete with a high steel-bar reinforcement percentage will lead to an optimized technical solution in order to achieve high performance structures.

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