Impact Response of Different Classes of Fibre Reinforced Concrete

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Abstract. The use of fibre reinforced concrete in structural elements exposed to impacts or different types of extreme loading represents one of the main fields of application of this high-performance material. Nevertheless, there is not a general consensus about a test for impact characterization of fibre concretes and, specifically a procedure to evaluate the contribution of fibres after cracking. It is well known that fibres control the evolution of cracks, improving the durability of concrete elements. Nowadays there are many structural fibres available; one of the greatest advantages to enhance the use of different fibres is the introduction of FRC classes in the fib Model Code 2010. However, there are not references about the relationship between the residual capacity measured in static tests (i.e. EN 14651) and the impact response. A drop weight impact test method is proposed to evaluate the contribution of different fibres considering both the cracking resistance and the behaviour in cracked state. Results of FRC belonging to different classes, incorporating different contents of steel, glass and polymer macrofibres are presented and compared. The effect of the residual capacity measured on standard bending tests on the impact resistance is discussed.

Keywords: Crack control · FRC class · Impact tests · Glass macrofibres · Polymer macrofibres · Steel fibres

1 Introduction

The benefits of using Fibre Reinforced Concrete (FRC) in structural elements exposed to explosions, vibrations, ballistic shocks and different types of impact [1–7] have been confirmed. Although numerous methods have been proposed [8–12] there is no a general consensus about a method to characterize the impact response of FRC.

Considering that the main contribution of fibres takes places after the initial cracking of concrete matrix, it is interesting to develop a procedure for evaluating the impact resistance in FRC at the cracked state. As nowadays many different types of fibres are available their performance in the presence of impact loads becomes of great interest.

Using a single drop-weight impact instrumented test Banthia et al. [13] compared the flexure impact resistance of plain concrete, steel and polypropylene FRC concluding that 0.5% in volume of polypropylene fibres increases around 50% the fracture energy and 1.5% of steel fibres triplicated it. Bindiganavile et al. [14, 15] developed fibre-matrix bond impact tests and bending impact tests on FRC prepared with polymeric and steel fibres; it was found that at high rates both fibres increased bond strength, but at very high velocities steel fibres presented lower bond and energy absorption capacity than the polymeric fibres; similar trends were observed in bending impact tests. Testing steel, polypropylene and cellulose FRC by using the impact tests proposed by the ACI committee 544 [16] it was observed that while the first crack strength increased when cellulose fibres were incorporated, the use of polypropylene fibres improved the post-crack behaviour.

As it is known, there can be quite different post-cracking behaviours in FRC. In addition to the material with which the fibres are made (steel, polymer, etc.), many factors as geometry, stiffness, strength and interface bond as well as the concrete matrix characteristics can affect the composite response. In this way, there is a general agreement that fibre performance must be valued by the FRC residual capacity. Considering the huge alternatives of fibres for concrete reinforcement, the fib Model Code 2010 [17] established FRC classes based on the residual stresses determined using the EN14651 standard bending test [18].

In this paper a simple drop-weight test was implemented in order to explore the relationship between the static residual capacity and the impact resistance. Different classes of FRC incorporating different contents of steel, glass and polymer macrofibres as well as the corresponding base concrete without fibres were evaluated.

2 Experimental Program

2.1 Impact Test

With the aim of evaluating the impact resistance, both considering first crack and the post-cracking behaviour, a repeated drop-weight test was implemented. In preliminary experiences several alternatives for loads application and specimen geometry were explored, as well as the variability of results and the minimum number of specimens required and different parameters for impact resistance characterization [19].

Considering that one of the motivations of the research was to study the relationship between the residual capacity measured in static standard tests and the impact resistance, prismatic specimens of $150 \times 150 \times 300$ mm were selected for the tests, which may be the halves resulting from the bending characterization test (EN 14651), with a 25-mm depth notch at the centre of the tensile face. As was confirmed in a previous study, using this notch depth no shear failure occurs. The use of prisms of the same section for static and impact tests avoids differences in fibre orientation due to the mould geometry.

The impact test procedure and instrumentation is relatively simple and consists on repeated drops of a projectile (with a mass m) on the top of the specimen from a certain height (h). After each impact, Crack Opening Displacement (COD) was measured at

120 mm below the top face of the prism using a Dino-Lite Premier digital micro-scope® AM4113T, 1.3 Megapixels, which with the provided software, makes possible to measure elements with a precision of 0.0001 mm.

The impact testing device was done by adapting an equipment originally designed for drop-weight tests on steel specimens [20, 21]. The system has two vertical steel rails to guide the projectile; when it achieves the desired height, it is released and impacts the specimen at the middle span. Figure 1 shows a general view of the machine and some setup details; the projectile adopted for this study has 5 kg-mass, 150 mm width and semi-circular section linear Tup (striking end of the projectile).
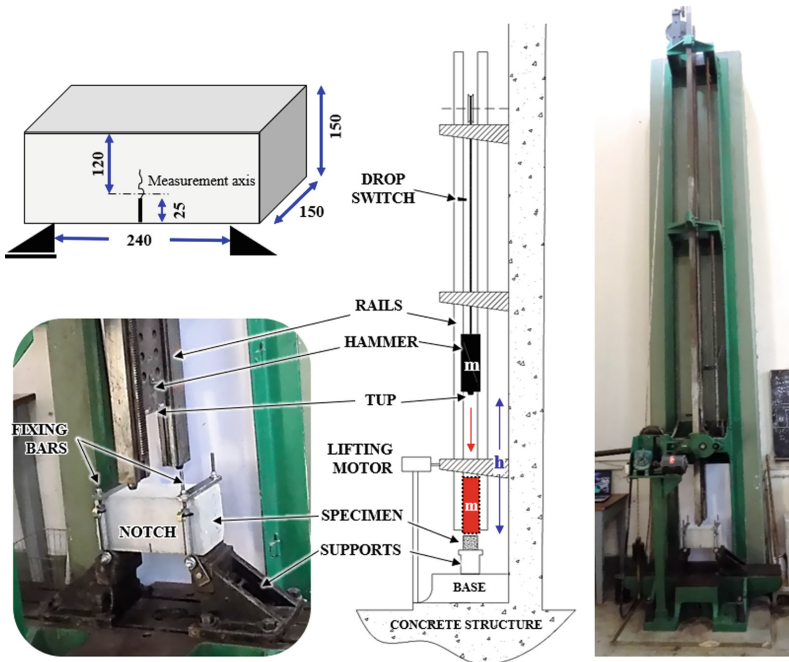

Fig. 1. Impact testing device (values in mm).

The prism rests on cylinders that allow the sample to rotate at the plane of impact; each support has a metallic bar that fixes the prism and prevents lifting during and after each impact. One of the supports is fixed to the base while the other is left free (properly lubricated), so that it is allowed to move horizontally.

The impact test has two phases. In Phase 1, with the objective of determining the cracking resistance, impact loads are applied on a sound specimen; the drop height is progressively increased from an initial height (h_o) of 100 mm with height increments (Δh_o) of 50 mm; only one drop is applied for each height level and the process finishes when a visible crack (~ 20 µm) is detected. With the aim of evaluating the contribution of fibres in cracked state, Phase 2 starts using h_o equal to 100 mm and Δh_o 100 mm, but in this case three impacts are applied in each height level. The end of the test occurs

when the COD is greater than 3 mm. The heights gradual increase allows to evaluate concretes with different impact resistances; and the post cracking impact repetitions in each height level, prevents sudden leaps of energy, thus allowing a crack gradual opening and a greater sensitivity to perceive the effect of each type of fibre. This is useful specially when evaluating very low impact toughness concretes (or even in simple concrete), otherwise it is not possible to measure crack growth after the appearance of the first crack.

The energy of each impact is calculated as $m.g.h$ (being g the acceleration of gravity) and corresponds to the potential energy introduced to the system before starting the drop. The cumulated energy is the sum of energies of all impacts received by the specimen up to a certain point. The energy cumulated up to the first visible crack appearance, named cracking energy (E_C) and the initial visible crack opening (COD_C), are the impact test results from the Phase 1, while the post cracking energy (E_P), which is the cumulated energy between the first crack and the end of test (COD > 3 mm) and the COD rate during post-cracking (V_C), calculated from the cumulated energy between crack openings of 0.5 mm and 2.5 mm ($V_C = 2$ mm$/(E_{COD0.5mm} - E_{COD2.5mm})$, expressed in mm/J), are obtained for the Phase 2. Finally, the total energy E_T is also calculated as sum of E_C+E_P.

2.2   Concretes

A reference concrete (R) without fibres and six FRC incorporating steel (S), polymer (P) or glass (G) macrofibres were evaluated. The FRC were identified by a letter that corresponds to the type of fibre and a number indicating the fibre content (in kg/m^3). All mixtures were prepared using similar materials proportions using ordinary Portland cement, natural siliceous sand and 19 mm maximum size granite crushed stone. The water/cement ratio was 0.40. In Table 1 the used fibres characteristics are presented.

Table 1. Characteristics of fibres used.

Designation	S	G	P
Type	Steel	Glass	Polymer
Shape	hooked-end	flat	embossed
Length (mm)	50	36	58
Diameter (mm)	1.00	0.54	0.67
Tensile strength (MPa)	>1100	>1700	>640
Elastic modulus (GPa)	210	72	6.8

Three prisms of 150 × 150 × 600 mm and three cylinders of 100 × 200 mm were cast for each concrete mixture. All specimens were consolidated by external vibration, cured in a moist room for 28 days and then remained in laboratory indoor, to minimize the variation of concrete mechanical properties during the testing period. Firstly, both EN14651 bending [18] and ASTM C-39 [22] compression tests were carried out (at three months), and after that impact tests were performed.

3   Results and Discussion

Figure 2 shows the average stress-crack mouth opening displacement (CMOD) curves of each concrete. It can be seen that FRC with a wide range of static residual capacity were studied.
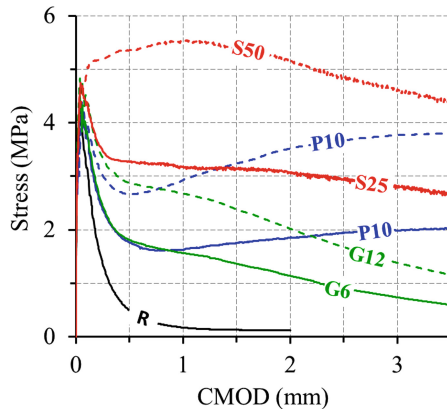
Fig. 2. Mean curves from bending tests performed in accordance to EN 14651.

Individual impact curves of concretes P5 and P10 are given in Fig. 3 as example. It can be seen that the curves are consistent within the same FRC with an acceptable variability in the post-cracking stage, which increases as the fibre content increases. In preliminary studies it was found that for an error lower than 15% and reliabilities of 90 or 95% the minimum number of specimens statistically required is 5 and 7 respectively.
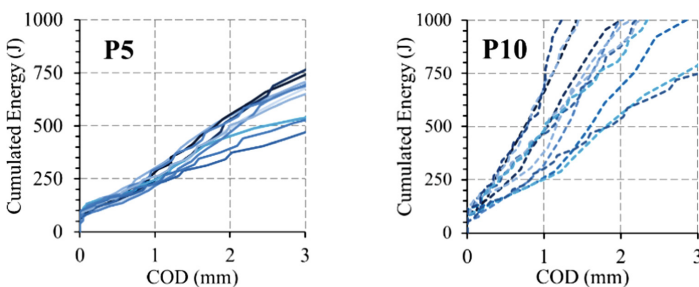
Fig. 3.   Individual impact curves for P5 (left) P10 (right).

Figure 4 (left) shows impact curves representative of each concrete, a higher slope implies a lower COD growth rate (V_C). Each symbol corresponds to one drop. When comparing the impact post-cracking response some differences in the shape of the curves can be seen. Concretes with steel fibres show a continuous progressive growth

and the V_C clearly decreases as fibre dosage increases. In G12 the cracking energy is lightly higher but later the crack control capacity decreases, resulting in lower energy compared with concretes incorporating other fibres. Polymer FRC show a particular response, for COD lower than 1 mm the shape of the impact curve is similar to the other FRC, between 1 and 2 mm a greater energy absorption capacity appears and, finally, once it is exceeded COD > 2 mm, the V_C increases again. The different responses not only depend on the material of the filament, they are significantly influenced by both the bond mechanism and the amount of fibres.
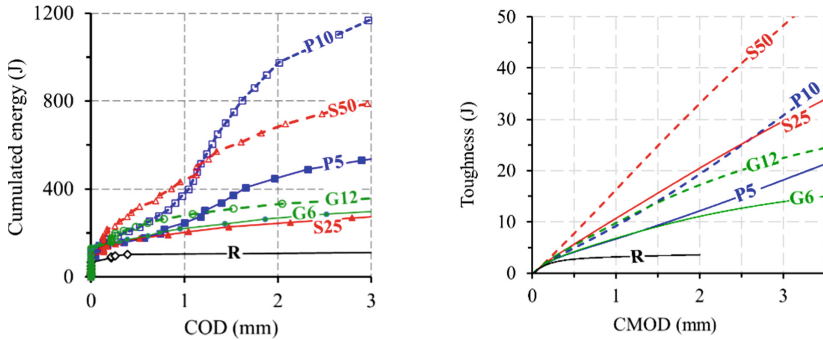
Fig. 4. Representative impact curves (left). Variation of toughness with CMOD during standard bending tests (right).

For comparison Fig. 4 (right) represents the evolution of static toughness (calculated as the area below the load-CMOD curve) evaluated from static bending tests. As expected, the values of energy are lower than those measured during impact tests; impact loads are applied during a very short time and also part of the energy can be dissipated by other mechanisms as vibrations or friction among others; it is well known that the cracks propagation is time dependent. Although in general terms for each FRC the increments in toughness are qualitatively consistent between static and impact tests, it can be seen that for great crack openings polymer FRC behaves better during impact tests than what could have been predicted based on static tests. While S25 or S50 achieved greater toughness in static bending than P5 or P10 respectively, the contrary occurs when the impact curves are compared. Even though, this situation could vary between fibres made of a same type of material, these results demonstrate that differential behaviours can appear. This highlights the necessity of a test for impact resistance evaluation.

Table 2 presents the mean values of compressive strength (f_c) as well as the first crack, or limit of proportionality (f_L) and the residual stresses f_{R1} and f_{R3}, corresponding to CMOD of 0.5 and 2.5 mm respectively, obtained in bending tests. In addition, the mean values of the cracking and post-cracking energies (E_C, E_P), the total energy (E_T), the initial visible crack opening (COD_C) and the COD growth rate (V_C) from impact tests are given. There are no significant differences in E_C between all concretes, indicating that it mainly depends on matrix strength. It was also confirmed that fibre incorporation reduces

the initial crack size even in the case of low toughness FRC. In the case of steel fibres although more energy was applied, the initial opening was smaller in S50 than in S25; in concretes incorporating polymer or glass macro fibres COD_C was greater for the higher dosages of fibres as greater impact energy was required to cause the initial crack as seen when comparing the corresponding E_C values.

Table 2. Summary of results from static and impact tests.

| Concrete	Static characterization						Impact test				
	f_c	f_L	f_{R1}	f_{R3}	f_{R3}/f_{R1}	FRC class	E_C	E_P	E_T	COD_C	V_C
	(MPa)						(J)			(μm)	(mm/J)
R	44.2	4.04	–	–	–	–	103	22	125	751	0.191
S25	44.5	4.75	3.27	2.93	0.89	3b	104	215	319	116	0.018
S50	44.8	4.42	5.36	4.87	0.91	5c	111	670	780	69	0.007
P5	47.3	4.38	1.77	1.94	1.10	2d	95	589	684	96	0.005
P10	46.3	4.21	2.67	3.67	1.38	2.5e	102	1183	1285	119	0.002
G6	47.1	4.51	1.81	0.90	0.50	2a	89	180	269	91	0.025
G12	46.6	4.83	2.88	1.67	0.58	3a	114	221	334	111	0.019

Analysing the results of V_C it appears that both in steel and polymeric FRC the COD growth rate decreases as the volume of fibres increases. The post cracking energy E_P is clearly associated with the COD growth V_C as shown in Fig. 5.
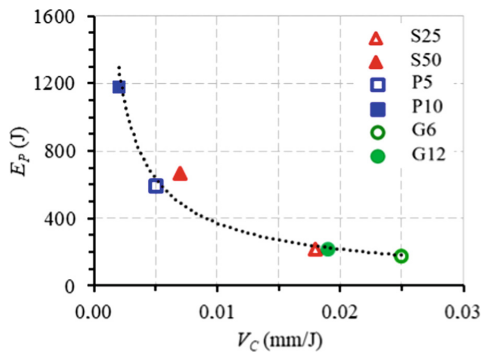
**Fig. 5.** Variation of post-cracking energy (E_P) with COD growth rate (V_C).

Figure 6 plots the relationship between the results of impact tests and the residual stresses f_{R1} and f_{R3}. Contrary to the case of E_C, which is practically independent of FRC toughness, it can be seen that as the residual stresses increase the total cumulated energy increases (Fig. 6 left). At the same time, although V_C decreases as FRC residual capacity

increases, as expected, its values depend on the fibre type, and polymer FRC showed V_C results clearly lower than those obtained with other types of fibres (Fig. 6 right).
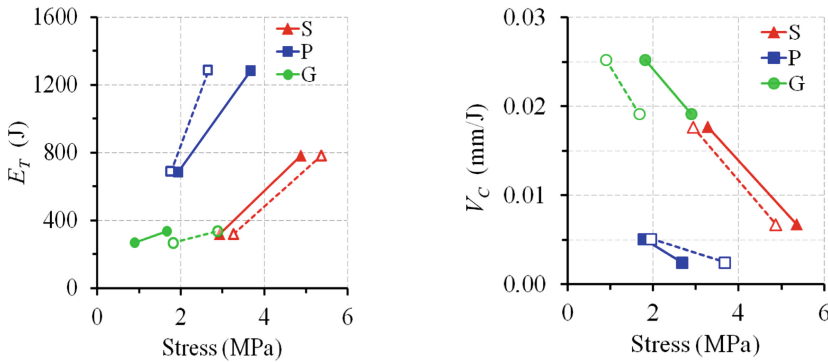
Fig. 6. Variation of E_T (left) and V_C (right) with the residual stresses f_{R1} (empty symbols) and f_{R3} (filled symbols) calculated from standard bending tests.

Figure 7 shows the influence of the residual stresses f_{R3}/f_{R1} ratio on impact test results: the measured energies and the COD growth rate. The dashed vertical lines indicate the limits for the f_{R3}/f_{R1} ratio (a, b, c, d, e) used to characterise the shape of the FRC post-cracking branch (hardening/softening) [17]. It should be noted that the FRC studied cover all of the post-peak responses established in this Code. It can be seen that as the residual stress ratio increases the cracking energy is not modified while the post-cracking energy (and consequently the total energy) clearly increases (Fig. 7 left). When the values of V_C are plotted against f_{R3}/f_{R1} ratio (Fig. 7 right), the rate strongly decreases ($R^2 = 0.88$). In both cases the results follow similar tendencies beyond the type of fibre used. This would appear as an additional advantage of the classification system adopted for FRC in the *fib* Model Code.
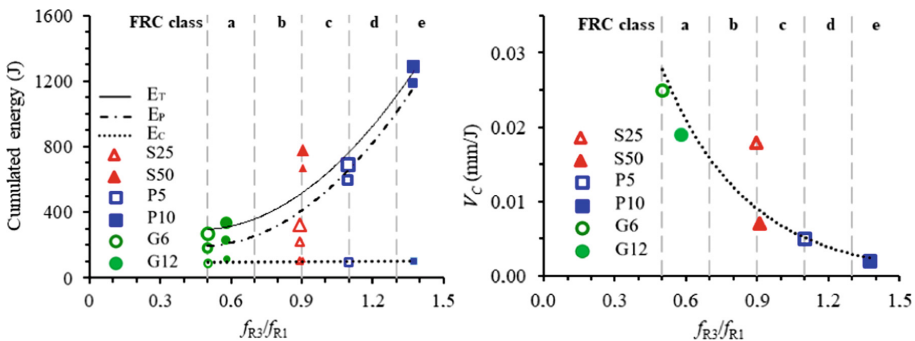
Fig. 7. Influence of f_{R3}/f_{R1} ratio on impact test parameters. Left: effects on cracking, post-cracking and total energies. Right: effects on V_C.

4   Conclusions

A drop-weight test on notched prisms was used to evaluate the contribution of different fibres on the impact resistance. Impact resistance was characterised in terms of cracking (E_C), post-cracking (E_P) and total (E_T) cumulated energy and the COD growth rate (V_C). Diverse classes of FRC obtained by incorporating different contents of steel, glass and polymer macrofibres were analysed. Main conclusions for the studied FRC are summarized as follows.

- A repeated drop-weight test was implemented which easily enables to evaluate both the resistance to the first crack and the behaviour in cracked state of fibre concretes. Impact test results among specimens of a same FRC show reasonable variability.
- The energy of cracking was not significantly affected by type and content of fibres. Nevertheless, fibre incorporation reduced the initial crack size even in the case of low toughness FRC.
- Increase in concrete impact toughness, expressed as total cumulated energy during impact test, were mainly observed after matrix cracking, and for steel and polymeric FRC.
- When comparing the post-cracking response some differences in the shape of the impact curves were found as a function of the material type of the fibres. Polymeric FRC were particularly efficient at large crack openings.
- A consistent relationship between the residual stresses measured in the static bending test and the post-cracking impact test results for the same fibre type was observed. As the residual stresses increase the total cumulated energy increases and V_C decreases.
- The results of V_C show an inverse tendency with the residual stresses ratio f_{R3}/f_{R1} beyond the type of fibre incorporated in concrete, which would appear as an additional advantage of the classification system adopted for FRC in the *fib* Model Code.

At the present, these findings correspond to the studied FRC and further studies are necessary for generalization of the conclusions. Experimental tests exploring the effects of concrete strength and other varieties of steel, polymer and glass macrofibres are in progress.

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