Composites Part B 183 (2020) 107680

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Functionally graded ultra-high performance cementitious composite with enhanced impact properties

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ARTICLE INFO

Keywords:
Functionally graded composite
Ultra-high performance concrete
Two-stage concrete
Slurry-infiltrated fibre concrete
Interfacial bond
Flexural property
Impact resistance

ABSTRACT

This study develops functionally graded ultra-high performance cementitious composite beams by applying the composite concepts of Ultra-high Performance Concrete (UHPC), Two-stage Concrete (TSC) and Slurry-infiltrated Fibrous Concrete (SIFCON). The functionally graded composite beam (FGCB) is fabricated with a bottom layer of SIFCON and top layer of TSC, and the two layers are synchronously cast by using UHPC slurry. The novel concept of FGCB is proposed towards more economical and high performance structural systems, namely excellent flexural bearing capacity and impact resistance, low cement consumption and high steel fibre utilization efficiency. The fresh and hardened properties of UHPC slurry, flexural and impact properties of FGCB are measured. The results reveal that the designed FGCB has superior flexural properties and impact resistance, without showing any interfacial bond problem. The fibre utilization efficiency of the designed FGCB is very high compared to the traditional UHPC and SIFCON beams. The 30 mm medium hook-ended steel fibres show the best utilization efficiency compared to the 13 mm short straight and 60 mm long 5D steel fibres, and 3% medium fibres are optimum to design FGCB. The low-velocity impact resistance of FGCB is well linearly correlated with its static flexural toughness.

1. Introduction

Concrete is one of the most widely used construction building materials in civil engineering. The brittle behaviour subjected to tensile or flexural loading is an adverse property, which causes negative influences, e.g. abrupt failure without warning, reduced service life due to crack formation and propagation. To overcome this shortcoming, fibre reinforced concrete was proposed by adding discrete steel fibres into plain concrete matrix [1,2]. In the 1990s, Ultra-high Performance Concrete (UHPC) was invented and further extended to the concept of fibre reinforced concrete (UHPFRC), which is characterized by high dosage of steel fibres, large amount of reactive powders without any coarse aggregate, and very low water content [3–5]. Although UHPC already possesses excellent microstructure, strength, durability, ductility and impact resistance [6–8], its tensile and flexural strengths are still relatively low, especially compared to the compressive performance [9–12]. In addition, the high content of steel fibres and reactive powders in UHPFRC have adverse impact, causing economic and environmental problems [13,14]. Thus, how to develop more eco-friendly UHPFRC materials and structures is of great interest for both researchers and engineers.

The aggregate-to-powder ratio is a key factor to determine the powder consumption and control the cost of UHPC. Recently, some researchers attempted to introduce coarse aggregates into UHPC system to reduce the powder content [15,16], enhance the impact resistance [7,17] and improve the volume stability [18]. Our previous study revealed that incorporating an appropriate amount of coarse aggregates with proper sizes could significantly reduce the powder content of UHPC, still possessing a comparable mechanical strength [15]. However, the coarse aggregates usually occupy limited volume, namely less than 40% of total UHPC matrix. To further enlarge the volume of coarse aggregates and diminish the powder content, we applied the two-stage concrete (TSC) concept in UHPC system, i.e. we first place coarse aggregates in mould and subsequently inject ultra-high performance slurry into the voids by gravity pressure [19]. The designed two-stage UHPC can significantly enhance the utilization potential of coarse aggregates, up to approximate 60%, which consequently greatly decreases the powder demand and creates great economic benefit [20].

The high strength steel fibre is another key factor to remarkably address the brittle behaviour of UHPC, however it is much more

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https://doi.org/10.1016/j.compositesb.2019.107680
Received 24 June 2019; Accepted 3 December 2019
Available online 6 December 2019

expensive than the other ingredients. Thus, it is of great significance to improve the fibre utilization efficiency of ultra-high performance fibre reinforced concrete (UHPFRC). Meng et al. [21] studied the rheology to control fibre dispersion uniformity, which improved the flexural performance of UHPFRC. Yoo et al. [22] suggested to use long steel fibres to enhance flexural properties. Controlling fibre orientation [23,24] and using hybridization [25] are also efficient measures to increase the utilization efficiency on both static and impact properties. Another solution to efficiently utilize steel fibres is to position more steel fibres into the tensile zones instead of compressive areas, due to the more remarkable reinforcement of steel fibres on tensile behaviour rather than compressive behaviour. According to this design concept, multiple layered (or functionally graded) concrete composites have been developed with good flexural performance, fracture energy, penetration impact resistance, as well as economical benefit [26–29]. However, the functionally graded concrete composites have potential interfacial bond problems, namely weak bond or even delamination in the case of casting the top layer on the hardened bottom layer [30], or wavy layers and uneven thicknesses in the case of casting the top layer onto the bottom layer that is still not hardened due to gravity force from the top layer [26]. Furthermore, sometimes high dosage of steel fibres is needed to achieve stronger and energy absorptive UHPFRC beams, especially for protective structures subjected to impact and blast loadings. It is rather difficult or even impossible to add a high volume fraction of steel fibre in the bottom (tensile) layer because of the workability reduction and 'balling' phenomenon [31]. Thus, it is reasonable to use Slurry-infiltrated Fibre Concrete (SIFCON) in the tensile layer, which can easily achieve fibre volume fraction up to 10% [32].

To develop a superior cementitious composite beam subjected to flexural and impact loadings, we propose a novel functionally graded composite beam (FGCB) concept by applying the combined concepts of UHPC, TSC and SIFCON. The bottom layer consists of SIFCON to withstand high tensile stress, while the top layer is designed by two-stage UHPC to achieve an excellent compressive strength with very low cement consumption. The UHPC slurry is injected into the voids of steel fibres (bottom layer) and coarse aggregates (top layer) simultaneously to acquire superior interfacial bond. The 13 mm straight, 30 mm hook-ended and 60 mm 5D steel fibres are investigated with volume fraction from 0 to 3%, in order to find an optimal type and content of steel fibre on the flexural and impact properties. Furthermore, the superior performance, low cement consumption and high fibre utilization of FGCB are revealed by comparing with conventional UHPFRC and SIFCON beams. An analytical predicting model of impact resistance by using the static flexural toughness is proposed and discussed.

2. Experimental program

2.1. Materials

The UHPC slurry is composed of Portland cement CEM I 52.5 R (PC), micro-silica (mS), limestone powder (LP), fine sand (S), tap water (W) and PCE-type superplasticizer (SP). The physical and chemical properties of those raw materials can be found in our pervious study [7,15]. The coarse basalt aggregate (BA) with particle sizes between 16 and 25 mm is selected by considering its high inherent strength and passing ability of slurry based on our preliminary tests, as shown in Fig. 1(a). Three types of steel fibres (SF) are used to investigate the type and dosage effect on the performance of FGCB. Table 1 and Fig. 1 (b) exhibit the characteristics of the utilized steel fibres.

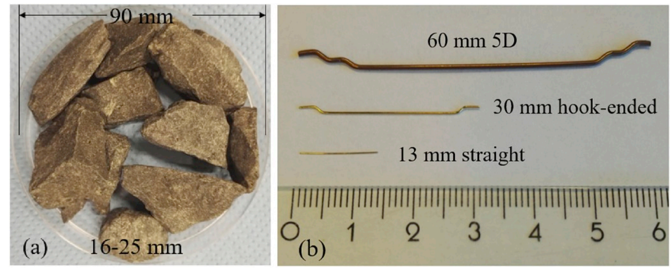

Fig. 1. (a) Basalt aggregates and (b) steel fibres.

2.2. Fabrication of FGCB

As illustrated in Fig. 2, the FGCB is fabricated by combining the bottom (SIFCON) and top (TSC) layers. The steel fibres are firstly placed in the steel mould, followed by coarse basalt aggregates above the steel fibres, then the UHPC slurry is injected into the voids by gravity pressure. Vibration is also applied to ensure a good quality of compactness. Because the steel fibres and coarse aggregates are well controlled and preplaced as a stiff skeleton, the phenomena of wavy layers and uneven thicknesses that usually occurs in the fresh state cast of conventional multi-layered concrete composites can be avoided. Furthermore, the slurry in both bottom and top layers is cast simultaneously, the interfacial bond strength should be much better than the cold bond in most multi-layered concrete composites.

Besides the properties of coarse aggregates and steel fibres, the whole performance of FGCB is strongly dependent on the properties of the slurry. To acquire a superior FGCB, the slurry is designed based on the UHPC system, which has both excellent fresh and hardened properties. Table 2 shows the mix proportion of the designed UHPC slurry. A PCE-type superplasticizer is utilized to achieve a desired fluidity with a dosage of 2% by the weight of total powder [33]. The optimal proportion of powders is 5% of micro-silica and 20% of limestone powder by mass of the total powder, by considering the flow ability, mechanical strength and drying shrinkage of UHPC pastes [15]. The fraction of fine sand is calculated based on the Brouwers method to achieve a good packing density with a particle distribution q of 0.22 [34–36]. The total particle size distribution of UHPC slurry is shown in Fig. 3.

The recipes of the designed FGCB can be seen in Table 3. Although the first mixture is a two-stage UHPC without fibre, it is also abbreviated as FGCB as a special case without SIFCON layer. The research parameters include steel fibre dosage (from 0 to 3 vol% by the total volume of FGCB) and type (13 mm straight (short), 30 mm hook-ended (medium), 60 mm 5D (long)). The binder (cement and micro-silica) consumption ranges approximately between 400 and 700 kg/m^3, which is much lower than conventional UHPC [5,37]. The cross-sections of the designed FGCB are presented in Fig. 4, which are cut from the hardened beams.

2.3. Experimental methods

2.3.1. Fresh and strength tests of slurry

The fresh behaviour of the UHPC slurry determines the casting quality of FGCB, which is measured by mini slump flow (without jolting), mini V-funnel flow time and fresh density, based on the EFNARC standard [38]. The compressive strength of hardened UHPC slurry greatly influences the whole flexural and impact properties, which is tested by cubic samples (50 × 50 × 50 mm^3) after 28 days, in conformity with the EN 12390-3: 2009 [39]. All the tests are conducted at room temperature of approximately 20 ± 1 °C.

2.3.2. Flexural test of FGCB

The central point flexural test is conducted for FGCB (100 × 100 × 500 mm^3) with a span of 300 mm after 28 days, based on the EN 12390-5: 2009 [40]. Fig. 5 shows the sample and set-up of central point flexural test. Fig. 6 illustrates the key parameters derived from the results of load-deflection curve. It can be divided into three stages, namely elastic stage (I), deflection hardening stage (II) and deflection softening stage (III). The elastic strength (σ_e) and peak strength (σ_p) are calculated from the elastic (P_e) and peak loads (P_p), respectively. The flexural toughness (T) is defined as the area under the load-deflection curve, which

Table 1
Characteristics of steel fibres.

Length (L) (mm)	Fibre shape	Diameter (d) (mm)	Aspect ratio (L/d)	Density (kg/m^3)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Number of fibres per kg
13	Short straight	0.21	62	7850	2750	200	27000
30	Medium hood-ended	0.38	79	7850	2300	210	3600
60	Long 5 D	0.9	65	7850	2300	210	2300

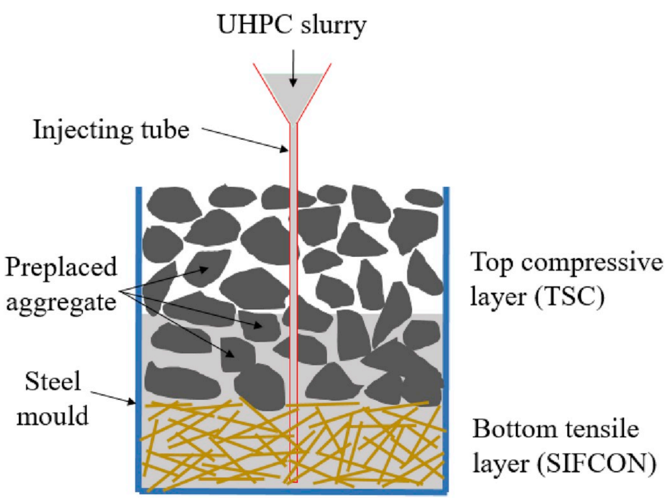

Fig. 2. Schematic picture of casting procedure.

Table 2
Mix proportion of UHPC slurry.

Materials	PC	mS	LP	S	water	SP
Volume fraction (%)	29.08	2.63	9.01	30.27	28.09	1.76
Mass proportion	0.75	0.05	0.20	0.66	0.23	0.02
Mass (kg/m^3)	916.1	61.1	244.3	808.1	280.9	21.1

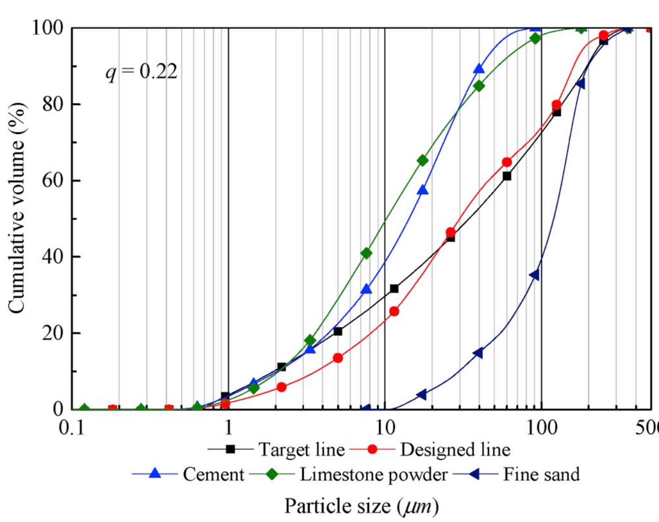

Fig. 3. The PSD of raw materials and designed UHPC slurry.

represents the energy absorption ability.

2.3.3. Drop-weight impact test of FGCB

To measure the impact resistance of cementitious based composite, some low-velocity impact testing methods are usually utilized, such as drop-weight impact test and pendulum impact test [41,42]. In this study, a drop-weight impact set-up is designed to research the impact resistance of FGCB, as presented in Fig. 7. A steel ball weighted as approximately 4.01 kg is held up by a magnetic device, and released from the height of 3.16 m. Then, the steel ball impacts on the top surface in the centre of FGCB with a span of 300 mm. The drop-weight impact is repeated till the fracture of FGCB, and the impact resistance can be described by the total absorbed energy (E),

Table 3
Recipes of the designed FGCB (UHPC slurry composition can be found in Table 2, BA is basalt aggregate with particle sizes between 16 mm and 25 mm).

Mix No.	UHPC slurry (binder) (kg/m^3)	BA (kg/m^3)	Fibre average dosage (vol.) & type
FGCB1	976.9 (408.9)	1825.9	0
FGCB2	1249.0 (522.7)	1427.8	2%, short
FGCB3	1447.3 (605.8)	1175.7	2%, medium
FGCB4	1357.6 (568.2)	1278.3	2%, long
FGCB5	1274.2 (533.3)	1414.0	1%, medium
FGCB6	1692.1 (708.2)	846.3	3%, medium

$$E = n \cdot mgh \tag{1}$$

where n is the total impact number till complete failure; m and h are the mass and impact height of steel ball, respectively; g is the gravity acceleration, 9.8 m/s^2.

3. Results and discussion

3.1. Fresh and hardened properties of slurry

The UHPC slurry is a critical factor for the overall performance of FGCB. The casting method and quality control of TSC and SIFCON are dependent on the excellent fresh behaviour of UHPC slurry. The fresh and hardened properties of UHPC slurry are presented in Table 4. In this study, the designed UHPC slurry has a mini slump flow of 39 cm and mini V-funnel flow time of 7.1 s, which satisfy the requirement of self-compacting, namely slump flow larger than 24 cm and V-funnel time shorter than 11 s [38,43]. Based on our preliminary tests, a UHPC slurry possessing mini slump flow beyond 35 cm has enough passing ability to fill the voids of aggregates by checking the apparent and cross-section characters. The fresh density and 28d compressive strength are approximately 2.3 g/cm^3 and 144.6 MPa, respectively, which meet the required high strength of UHPC system. To sum up, the UHPC slurry is successfully developed with both very good fresh and hardened properties, which will be utilized to design the FGCB.

3.2. Flexural properties of FGCB

3.2.1. Load-deflection curves

Fig. 8 presents the load-deflection curves of the designed FGCB based on central point flexural test. As illustrated in Fig. 6, a cementitious composite usually undergoes three stages under a flexural loading till complete failure. The plain FGCB without SIFCON layer only shows an elastic stage and ruptures abruptly when reaching the maximum flexural load (20 kN). Other designed FGCBs almost experience three stages, including elastic, deflection/strain hardening, and deflection/strain

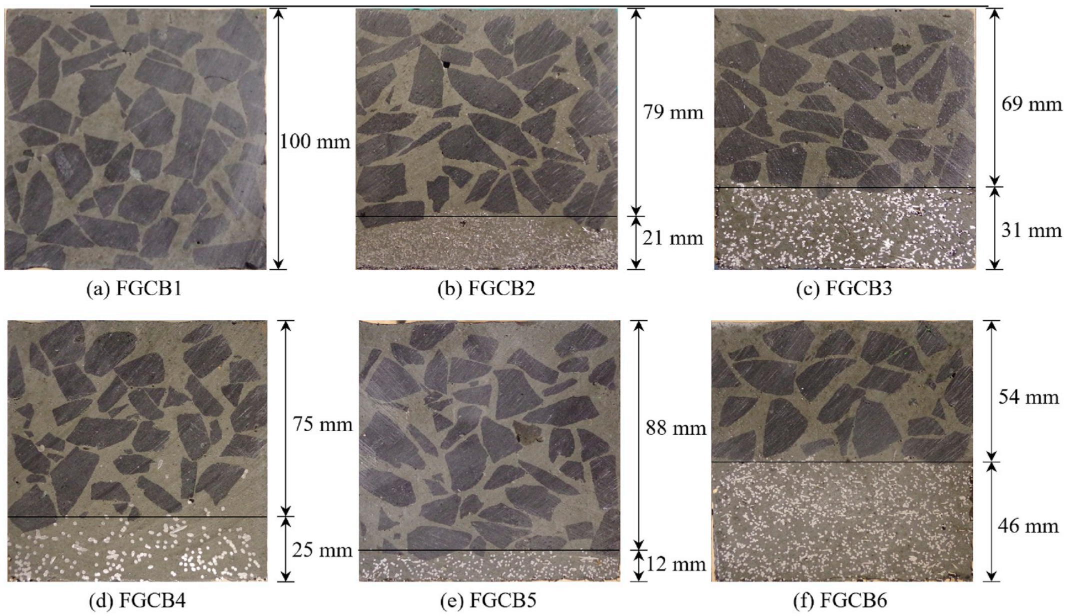

Fig. 4. Cross-sections of FGCB (total height = 100 mm, top layer is TSC, bottom layer is SIFCON).

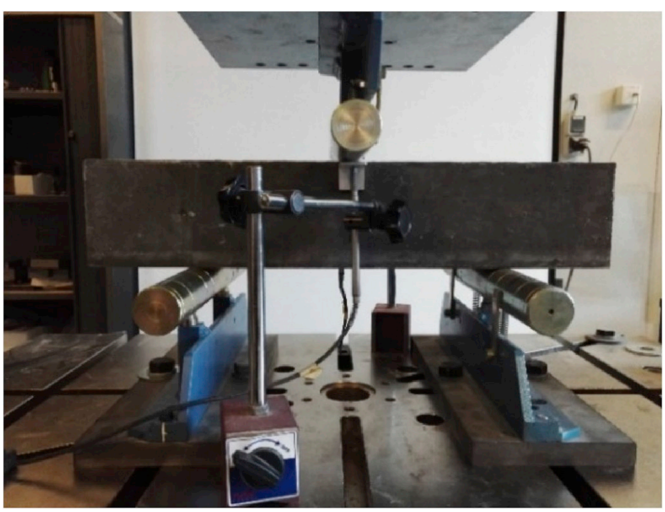

Fig. 5. Three-point flexural test.

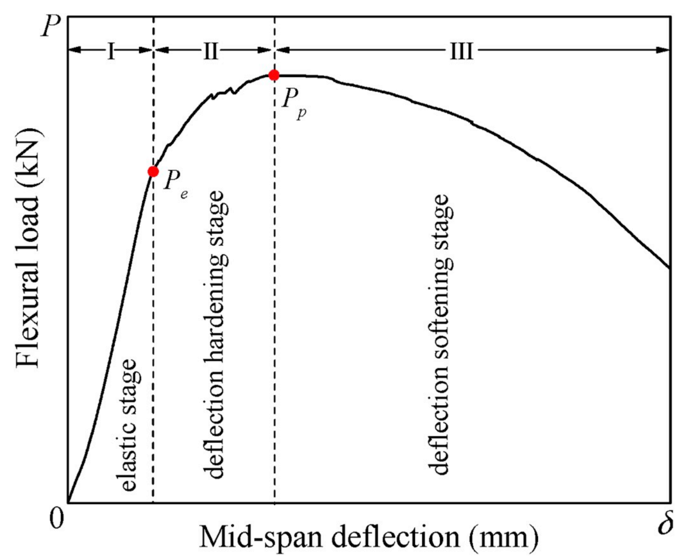

Fig. 6. Key parameters of flexural test.

softening stages. The first crack loads of FGCB, defined as the elastic load in Fig. 6, are not obvious. The elastic stage transits into the deflection hardening stage gradually after elastic load, which indicates that the ductility of the designed FGCB is good compared to other brittle cementitious composites. The 2% short and long fibres only provide limited deflection hardening behaviours compared to the medium fibres, and their residual bearing capacities can remain until the deflections of approximately 4 mm. For the medium hook-ended steel fibre, 2% volume dosage can trigger a considerable deflection hardening behaviour, and 3% volume dosage further improves this behaviour, and the residual bearing capacity can remain until the defalcation of around 8 mm.

With the inclusion of 2% steel fibres, the load-deflection curves of FGCB can be significantly enhanced for both peak load and toughness, as shown in Fig. 8 (a). However, the different steel fibre types show great difference. The 13 mm short straight fibres provide the poorest enhancement, with about 2.4 times and 15.4 times of peak load and toughness, respectively, compared to the plain FGCB without fibre. Followed by the 60 mm long 5D fibres, they offer slightly higher reinforcements on both strength and toughness. The 30 mm medium hook-ended steel fibres have the best reinforcing effect than the short and long ones, presenting approximately 3.3 times and 48.8 times of peak load and toughness, respectively, compared to the reference beam without fibre. The best reinforcing effect of medium fibres is attributed to the following aspects: (1) a good anchorage effect due to the hood-ended shape; (2) the highest aspect ratio that is usually positively linked to the reinforcement; (3) the largest distribution space because of the moderate length and number of fibres per kilogram, as shown in Fig. 4 (c), contributing to the largest tension resistant zone (SIFCON layer).

As analysed above, the 30 mm medium hook-ended steel fibres provide the best reinforcement on the flexural properties of FGCB. Hence, these steel fibres are chosen to investigate the fibre dosage effect. Fig. 8(b) presents the load-deflection curves of FGCB with different steel fibre dosages. With the addition of fibre dosage from 1% to 3%, the maximum flexural strength of FGCB shows almost linear improvement of 1.6 times, 3.3 times and 4.9 times as plain FGCB, while the

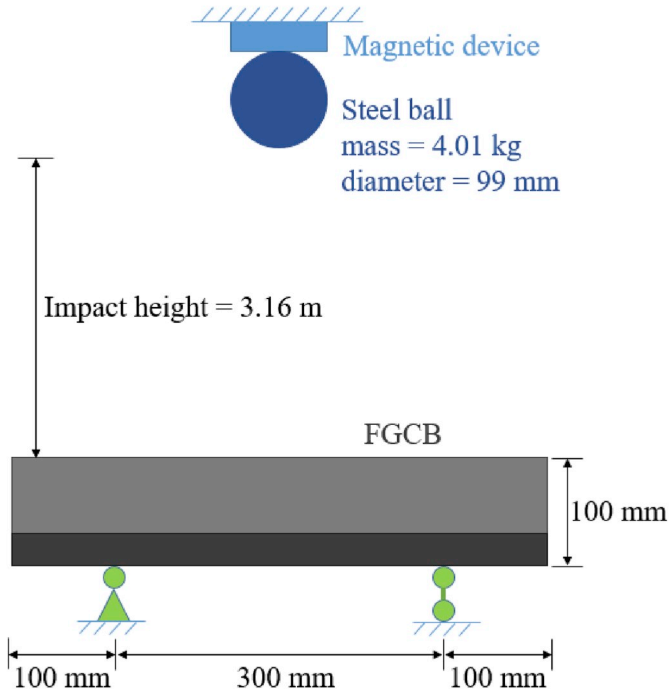

Fig. 7. Scheme of drop-weight impact set-up.

Table 4
Fresh and hardened properties of UHPC slurry.

Mini slump flow (cm)	$T_{v\text{-}funnel}$ (s)	Fresh density (g/cm^3)	28d compressive strength (MPa)
39	7.1	2.3	144.6 ± 2.1

enhancement on the flexural toughness is much more remarkable, namely 9.5 times, 48.8 times and 79.0 times, respectively. The thickness of the bottom (SIFCON) layer ranges from 12 mm with 1% fibres up to 46 mm with 3% fibres, so the bottom layer thickness ratio (β) is increased from 0.12 to 0.46. The β of approximately 0.5 was theoretically and experimentally confirmed to be the optimum by considering both flexural performance and fibre utilization, as illustrated in Fig. 9 [28,44]. Thus, 3% medium hook-ended steel fibres almost achieve the optimum layer thickness ratio β based on flexural properties and fibre utilization, which is suggested for designing FGCB in engineering applications.

3.2.2. Damage pattern and bond characteristic

The brittleness of conventional concrete beam usually results in one dominant crack damage pattern subjected to a flexural loading, which causes an abrupt failure of components or structures without warning. Hence, a multiple cracks damage pattern is more desired for cementitious composite beams, which is usually associated to the deflection or strain hardening stage [45]. Fig. 10 illustrates the damage patterns of the designed FGCB. FGCB with 2% short or long steel fibres has only one dominant crack from the centre of beam, which is similar to the plain FGCB. It agrees with the fact that the deflection hardening behaviour of those FGCB is not obvious, as shown in Fig. 8. With the inclusion of 1% medium steel fibres, the multiple cracks damage pattern or deflection hardening behaviour cannot be triggered. While, a number of micro-cracks can be observed for the FGCB with 2% medium steel fibres, as plotted by the red lines in Fig. 10. When 3% medium fibres are added, a much denser micro cracks on the surface occur, which is confirmed by the excellent deflection hardening behaviour and ductility.

The normal multiple layered or functionally graded concrete composites usually exhibit interfacial bond problems. The top layer is normally cast 24 h after the cast of the bottom layer (so called cold cast), resulting in a weaker interfacial bonding strength or even delamination due to different shrinkages and poor old-to-new hydration production integration [30]. Casting the two layers simultaneously or within a very short time interval (so called hot cast) can achieve a higher interfacial bond than the cold cast [28]. But it is well possible that wavy layers and uneven thicknesses are generated, because of the gravity load from the top layer on the bottom layer [26]. Those adverse interfacial problems could possibly cause debond phenomenon (delamination) and influence the flexural bearing capacity suffered from flexural loading [46]. The delamination has never occurred during the flexural tests for all the designed FGCB in this study, as shown in Fig. 10. The excellent interfacial bond of the designed FGCB is attributed to: (1) well controlled and preplaced stiff skeleton of the steel fibres and coarse aggregates; (2) very low shrinkage of both TSC and SIFCON; (3) same slurry and synchronous hydration for the two layers.

3.2.3. Fibre utilization efficiency

As analysed above, the reinforcement degree of steel fibre on flexural properties is significantly influenced by the fibre characteristics, such as fibre content and shape [45,47–49]. Furthermore, the cost of 1% volume content of fibre applied in concrete composites is generally higher than that of plain matrix [50]. Thus, it is important to enlarge the fibre utilization efficiency, or in other words, to minimize the amounts of fibre without sacrificing the superior performance of concrete composites. To study the steel fibre utilization efficiency on the flexural strength and toughness, a reinforcing factor η, defined as the normalized

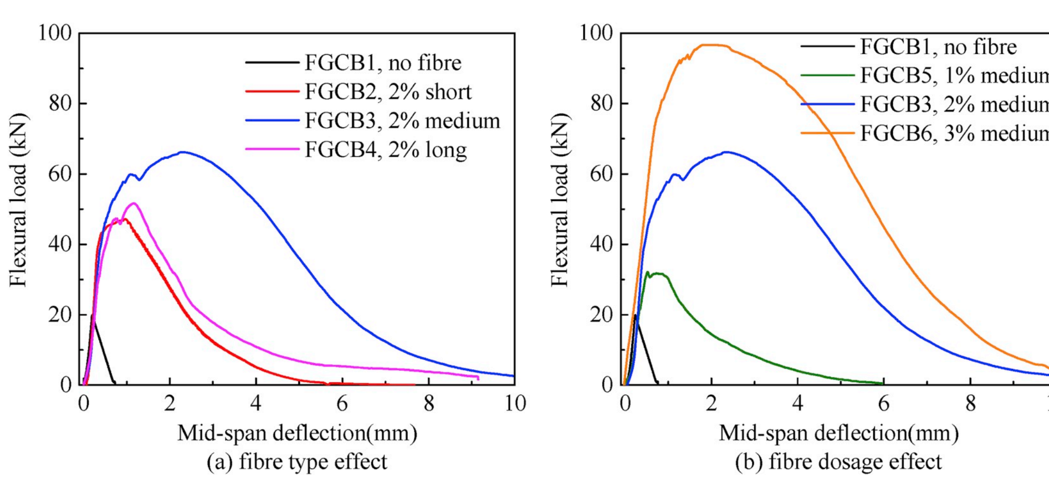

Fig. 8. Flexural load vs. deflection curves of FGCB.

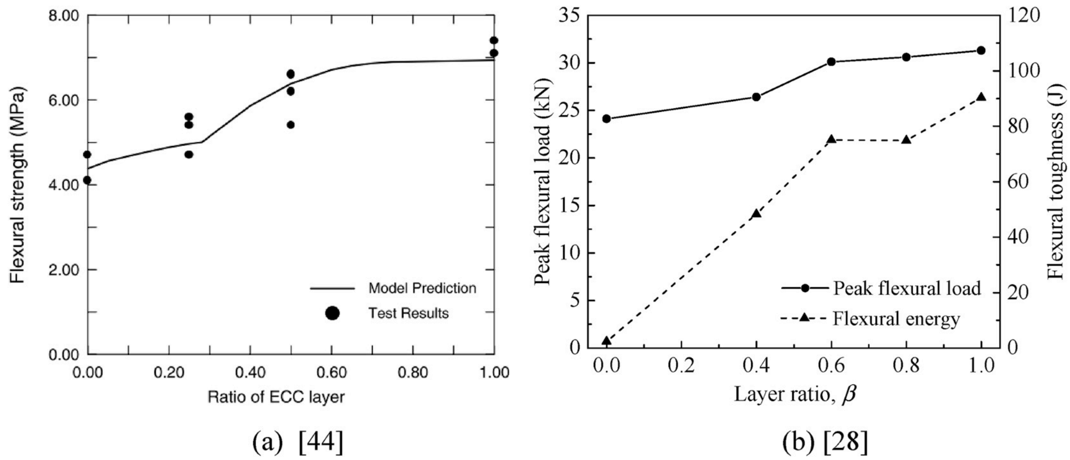

Fig. 9. Flexural strength/load and energy with different bottom layer thickness ratios.

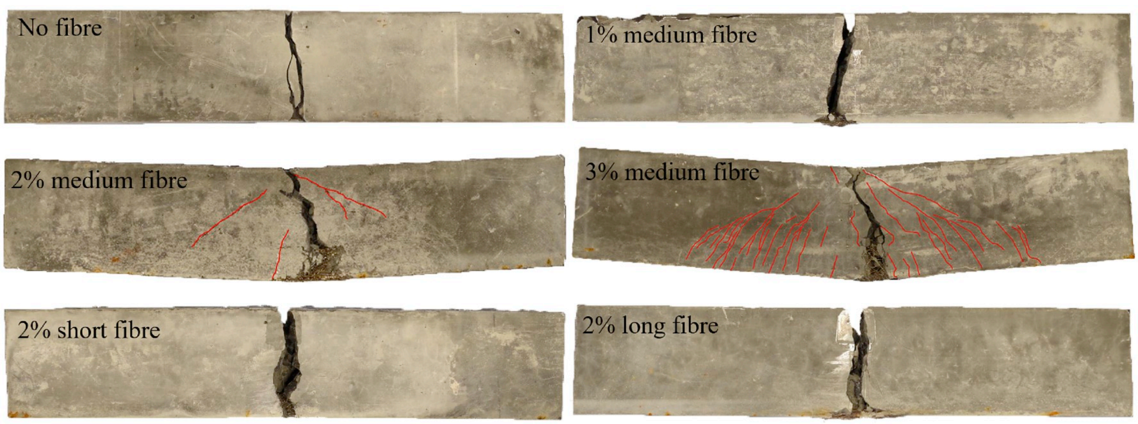

Fig. 10. Damage patterns of FGCB after flexural tests (see the compositions in Table 3).

improvement ratio by steel fibre volume content V_{fibre}, is proposed,

$$\eta = \frac{X_{FGCB}}{X_{plain}} \cdot \frac{1}{V_{fibre}} \tag{2}$$

where X_{FGCB} and X_{plain} respectively represents the flexural properties with fibres and without fibres, namely flexural strength and toughness in this study.

Fig. 11 shows the steel fibre type effect on the flexural strength and toughness of the designed FGCB. The 2% medium steel fibres provide the largest flexural strength (29.8 MPa), followed by the long fibres (23.2 MPa) and short fibres (21.2 MPa). Based on the flexural strength of plain beam (9.0 MPa), the reinforcing factors in term of strength (η_σ) are ordered as 1.66×10^2, 1.29×10^2 and 1.18×10^2, respectively. The fibre reinforcing effect on the flexural toughness has a similar trend to that of the flexural strength, while the reinforcing factors in terms of toughness (η_T) are much more remarkable, namely 24.4×10^2, 10.6×10^2 and 7.7×10^2, respectively. It indicates that both flexural and toughness are greatly dependent on the steel fibre types, while the contribution of fibres to toughness is more prominent. Furthermore, the 30 mm medium hook-ended steel fibres is appropriate and recommended to develop the FGCB, especially for the energy absorption ability.

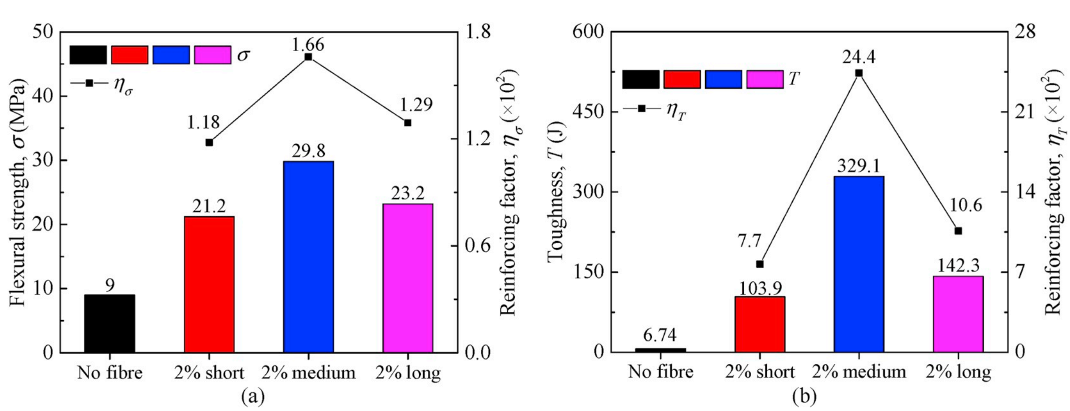

Fig. 11. Steel fibre type effect on flexural strength and toughness of FGCB.

Fig. 12 presents the dosage effect of 30 mm medium steel fibres on the flexural strength and toughness of the designed FGCB. 1% medium fibres addition can improve the flexural strength from 9 MPa to 14.4 MPa, while much more considerable flexural strength is achieved up to 43.5 MPa with 3% medium fibres. The flexural properties of the designed FGCB are more superior to those of most UHPFRC beams that usually have flexural strengths around 20–30 MPa [14,22,25]. Furthermore, the reinforcing factor η_σ keeps a stable level in the range of 1.6×10^2–1.66×10^2, which indicates that the increased dosage of medium fibres continuously improves the flexural strength without sacrificing fibre utilization efficiency. As seen from the load-deflection curves in Fig. 8, a much more significant improvement of medium fibres on toughness rather than strength is observed, with the reinforcing factor η_T increasing from 9.5×10^2 at 1% to 24.4×10^2 at 2%, then up to a slightly higher value of 26.3×10^2 at 3%. A higher dosage of medium steel fibres in the studied range always gives a higher fibre utilization efficiency on toughness. The 2% medium fibres increase the utilization efficiency significantly compared to the 1%, but 3% addition seems not to enlarge the fibre utilization efficiency too much. Yoo et al. also found that 3% steel fibre yielded the best mechanical properties, volume stability and fibre-to-matrix interfacial bond [51]. Thus, a dosage of at least 2% and up to 3% medium fibres is recommended for designing FGCB.

As analysed above, 2%–3% 30 mm medium hook-ended steel fibres are suggested to develop FGCB, considering both performance and fibre utilization efficiency. Because the steel fibres are added in the tension zone instead of the compression zone, the fibre utilization efficiency of the designed FGCB would be very high, which certainly contributes to the economic benefits and performance. To further demonstrate this advantage in FGCB, the fibre reinforcing factors η_σ of the designed FGCB are compared with other homogenous UHPFRC [14,52–54] and SIFCON [55] beams, as shown in Fig. 13. Normally, with the increase of steel fibre dosage, the utilization efficiency of UHPFRC beam tends to decrease, from approximately 1.32×10^2 at 1% to 0.63×10^2 at 6%. Additionally, the mixing and workability usually would become an issue when the fibre addition is beyond 3% in UHPFRC. Although the SIFCON beams can utilize very high volumes of steel fibre without mixing and workability problems, usually more than 6%, they achieve even much lower utilization efficiencies. While, the utilization efficiency of the 30 mm medium hook-ended steel fibres is very high compared to the UHPFRC and SIFCON beams, beyond 1.6×10^2 without any diminishing trend with the increase of fibre dosage from 1% to 3%. Therefore, the designed FGCB not only has superior performance but also possesses excellent fibre utilization efficiency and economic benefits.

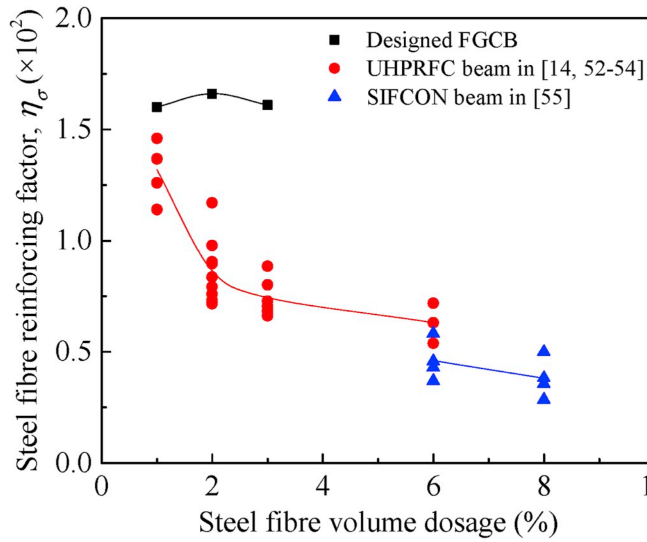

Fig. 13. Steel fibre utilization efficiency in term of flexural strength.

3.3. Impact properties of FGCB

3.3.1. Impact number and energy dissipation

The excellent flexural toughness shown by the designed FGCBs demonstrates that they possess excellent energy absorption capacities, which indicates that they are suitable to be applied in impact resistant components and structures. The impact resistance of the designed FGCB is described by the failure impact number and total energy dissipation under the drop-weight impact test, as seen in Table 5. The reference FGCB is very brittle and broken into two parts from the centre after only one impact (124 J), as shown in Fig. 14(a). Nevertheless, the impact resistance of the designed FGCB is considerably improved and can withstand multiple impacts. An example of the failure pattern of FGCB with steel fibres is illustrated in Fig. 14(b). The 30 mm medium hook-ended steel fibres provide the best reinforcement on the impact resistance of the designed FGCB, which is in line with the results of flexural properties. The FGCB incorporating 13 mm short straight and 60 mm long 5D steel fibres only provide about half the energy dissipation of the 30 mm medium hook-ended fibres in the case of 2% volume dosage. With the increase of medium steel fibre dosage from 1% to 3%, the

Table 5
Failure impact number and energy dissipation.

Mix No.	Fibre content and type	Failure impact number	Energy dissipation (J)
FGCB1	0	1	124
FGCB2	2%, short	30	3720
FGCB3	2%, medium	64	7936
FGCB4	2%, long	29	3596
FGCB5	1%, medium	8	992
FGCB6	3%, medium	82	10168

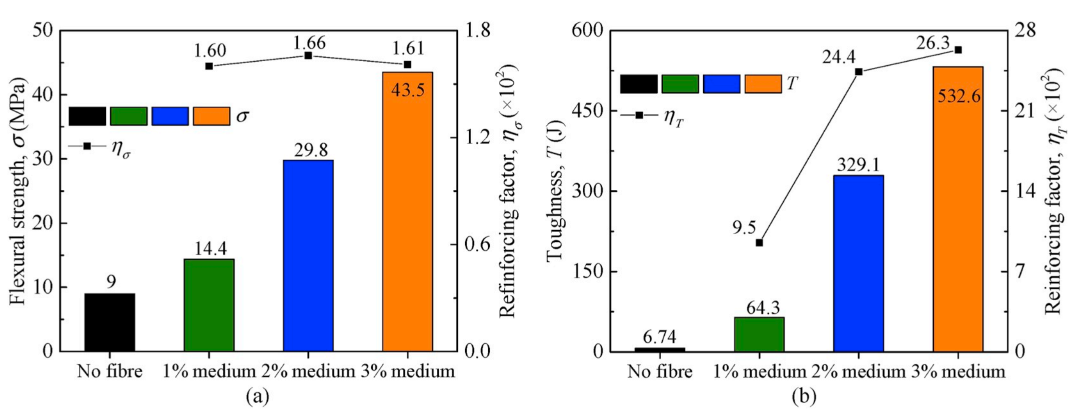

Fig. 12. Steel fibre dosage effect on flexural strength and toughness of FGCB.

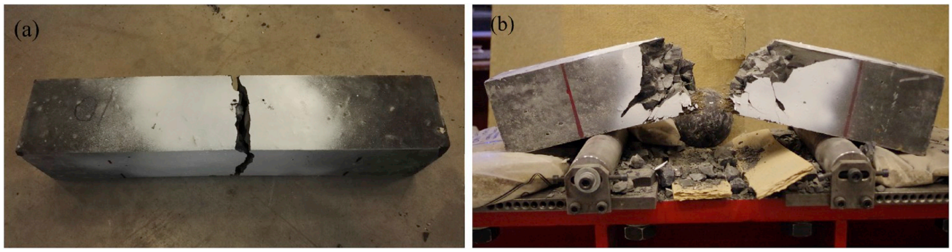

Fig. 14. Failure after impact tests: (a) FGCB1 and (b) FGCB5.

failure impact number is enlarged from 8 times to 82 times. To sum up, the designed FGCB with 3% medium fibres has superior impact resistance and is appropriate for applications in protective materials and structures.

3.3.2. Predicting impact resistance by flexural properties

As can be seen from Fig. 8 and Table 5, the steel fibres have a similar reinforcing trend on flexural properties and impact energy dissipation. Therefore, it is postulated to predict the impact resistance by flexural properties, which is much easier and more economical to provide guidance for both researchers and engineers [56]. Some attempts have been conducted to derive relationships between dynamic and static properties [7,56–58]. Our previous research explored the correlation between the residual impact resistance of UHPFRC beam and residual flexural strength, rigidity and toughness. Based on the analysis of damage indexes and physical significance, the flexural toughness is a good indicator for impact resistance and shows a linear relationship [7].

In this study, the impact resistance (E) of the designed FGCB is also associated to the flexural toughness (T), as shown in Fig. 15, and a linear equation is proposed to describe this relationship;

$$E = k \cdot T \tag{3}$$

The correlation coefficient k is approximately 21.02 ($R^2 = 0.97$). A similar linear trend is also observed in our previous researches on unnotched beam (150 × 150 × 550 mm^3) under pendulum impact energy of 689 J and notched beam (150 × 150 × 550 mm^3) under pendulum impact energy of 346 J (see Fig. 15) [7,59]. Thus, the flexural toughness seems always to be a good indicator for the impact resistance of an ultra-high performance cementitious composite beam under different low-velocity impact tests, and a linear correlation exists. It is noted that the value of correlation coefficient k varies greatly, which are linked to the beam type and size, support and boundary condition, impact energy and contact pattern. Overall, the impact resistance of the designed FGCB is well linearly predicted by the static flexural properties, which is around 21 times of the flexural toughness.

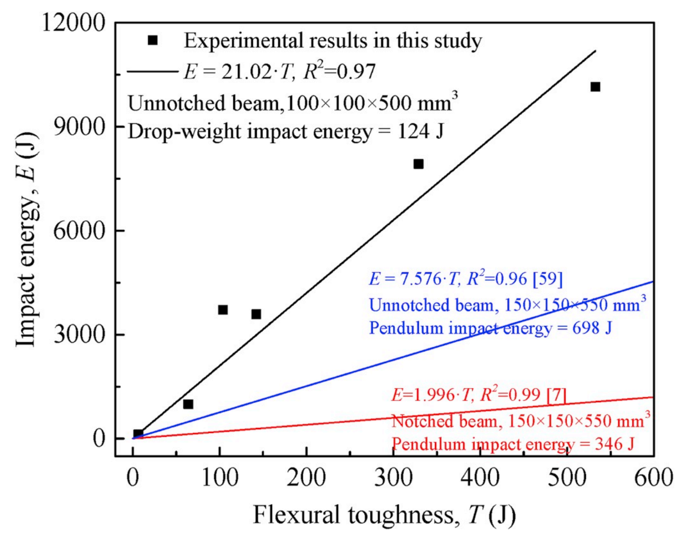

Fig. 15. Correlation between impact resistance and flexural toughness.

4. Conclusions

The paper aims to develop a novel FGCB towards superior flexural and impact properties by applying the composite concepts of UHPC (slurry), TSC (top layer) and SIFCON (bottom layer). The fresh and hardened properties of UHPC slurry, flexural and impact resistance of the FGCB, cement consumption and steel fibre utilization efficiency are explored and discussed. The following main conclusions can be summarized based on the results:

- A novel FGCB is successfully developed by combining the concrete of UHPC (slurry), TSC (top layer) and SIFCON (bottom layer), which has superior flexural and impact properties, strong interfacial bond, very low cement consumption and high steel fibre utilization efficiency.
- The UHPC slurry with excellent workability and strength is injected into the coarse basalt aggregates and steel fibres synchronously, avoiding uneven thicknesses phenomenon and weak interfacial bond problem that usually occur in the normal multi-layered concrete composites.
- The 30 mm medium hook-ended steel fibres show the best utilization efficiency than the 13 mm short straight and 60 mm long 5D steel fibres. 3% 30 mm hook-ended fibres are suggested to design FGCB with an optimum bottom-to-top layer ratios β of 0.46, considering both performance and fibre utilization efficiency.
- The binder consumption of FGCB is much lower than normal UHPFRC beam, ranging between 400 and 700 kg/m^3. The steel fibre utilization efficiency of FGCB is beyond 1.6 × 10^2, which is much higher compared to the homogenous UHPFRC and SIFCON beams. Both low binder consumption and high steel fibre efficiency contribute to economic benefits.
- The designed FGCB has superior impact resistance and is appropriate for protective materials and structures. The impact resistance under low velocity is well linearly predicted by the static flexural properties, which is around 21 times of the flexural toughness in this study.

Acknowledgements

This research is supported by the China Scholarship Council and Eindhoven University of Technology. The authors thank Mr. Gang Liu and Ms. Yangyueye Cao for their help with experiments. The authors also express their gratitude to ENCI, Bekaert and Sika for supplying the cement, steel fibres and superplasticizer, respectively.

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