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Sustainable development of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC): Towards to an optimized concrete matrix and efficient fibre application

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ABSTRACT

This paper addresses the sustainable development of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC). In general, based on theoretical and practical points of views, two strategies are employed here: 1) optimized design of the UHPFRC matrix based on modified Andreasen & Andersen particle packing model and appropriate application of substitutive materials; 2) efficient improve the fibre efficiency based on an optimized casting method. The obtained experimental results show that by utilizing the improved packing model and appropriate substitutive materials, it is possible to design a dense UHPFRC skeleton with relatively low binder amount, and the embedded CO_2 emission of the designed UHPFRC matrix can be effectively reduced. Moreover, based on the adjustment of fresh UHPFRC flowing parameters (such as flowing direction, flowing distance), the fibres orientation can be controlled, and an optimized UHPFRC with better mechanical properties can be obtained. Additionally, when the particle packing model, substitutive materials and controlled casting method are well utilized together, an optimized UHPFRC with low environmental impacts and high materials efficiencies can be obtained, which could promote a cleaner construction production in the near future.

1. Introduction

Nowadays, the sector of building materials (mainly cement based materials, as concrete) is the third largest CO_2 emitting industrial sector world-wide (UNSTATS, 2010), as well as in the European Union (Friedlingstein et al., 2010), and the cement production represents about 7% of the total anthropogenic CO_2 emissions (Capros et al., 2001). Therefore, to achieve a sustainable development of concrete industry and help the societies become more eco-friendly, one of the promising approaches is to design and produce a type of concrete with less clinker (Yu et al., 2015), inducing lower CO_2 emissions than traditional ones (Igliński and Buczkowski, 2017), while providing the same reliability and durability (Mohammadhosseini et al., 2017).

Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) is a relatively new construction material, which is a combination of high performance concrete matrix and fibres (Richard and Cheyrezy, 1995). Considering the successful application of UHPFRC in practice (e.g. Mediterranean Culture Museum in Marseille of France, Gärtnerplatz bridge build in Kassel of Germany), UHPFRC seems to be one of the most suitable candidates to reduce the global warming impact of construction materials (Habert et al., 2012). Due to the advanced mechanical properties and durability, the structure made of UHPFRC can be much more slender compared to normal concrete structure. One example is illustrated in Fig. 1 (Voo et al., 2012), noticeable difference between conventional reinforced concrete and UHPFRC, that are used for the construction of a L-shaped wall meeting the same project requirements, can be observed. In this case, the UHPFRC solution requires 73% less materials than the ordinary steel rebar reinforced wall. Thus it weighs 260 kg/m, much less than the 1200 kg/m of the wall constructed with conventional reinforced concrete. However, the disadvantage of UHPFRC in reducing its environmental impacts can also be noticed. Based on available literature (Tayeh et al.,

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Fig. 1. Difference in sectional dimensions of an L-shaped wall, made of conventional concrete and UHPFRC (Voo et al., 2012).

2012), when producing UHPFRC, the binder and fibre contents are normally relatively high (Hassan et al., 2012), and in most cases, the binders and steel fibres are added directly into concrete without clear explanation or theoretical supports (Rossi, 2013). Therefore, it can be predicted that efficiencies of used binders and fibres in the UHPFRC are relatively low, and the production of UHPFRC needs to be cleaner for the further development. Nowadays, as the sustainable development is currently a crucial global issue, high material cost, high energy consumption and high embedded CO_2 for UHPFRC are the typical disadvantages that restrict its wider application. There is an urgent need to develop a more sustainable and cleaner UHPFRC.

Based on available literature, it has been demonstrated that the hydrated cement amount is only about 40% of the used cement (Neville, 1995), or even less (Tuan et al., 2011a; 2011b). Most of the cement particles just act as filler or inactive material, which can be treated as one of the main reasons of why UHPFRC has relatively high materials and energy cost. Hence, it is logic to reasonably replace the un-hydrated cement particles with cheaper filler or unactive materials, without sacrificing the properties of UHPFRC. As commonly known, an optimum packing of the granular ingredients of concrete is the key for a good (Brouwers and Radix, 2005), durable (Hüsken and Brouwers, 2008) or sustainable concrete (Quercia et al., 2012). A reduction in the cement content should be possible in practice by using inert filler materials, while these filler materials have to be implemented in the entire grading of the mix together with the binding materials in order to achieve densest possible packing. The optimized particle packing can result in a denser granular structure of the aggregates used and therefore less binding materials are needed. This owing to the denser granular structure also the mechanical properties as well as the porosity of the final product will be improved. At present, to effectively replace the unhydrated cement in UHPFRC, different powders seems to be useful either as inert fillers or pozzolanic materials, such as ground granulated blast-furnace slag (GGBS), fly ash (FA), limestone powder (LP) and so on. Some available literature show that these powders have different effect on the properties of concrete, such as cement hydration (Yang et al., 2016), mechanical properties development (Medina et al., 2017) and sustainable properties (Yang et al., 2015). Consequently, an appropriate mix design of UHPFRC matrix skeleton based on particle packing model and substitutive materials is a potential method to reduce its environmental impact. Nevertheless, a systematical analysis of the eco contributions of optimized design and different substitutive materials (separately or combined) on the sustainable development of UHPFRC is still needed.

In the production of UHPFRC, the added fibres (most likely steel fibres) also play a very important role in improving its mechanical properties. However, in most cases, the fibres are added into the concrete directly and randomly (similar as black box treatment) (Hassan et al., 2012), and the fibre meso-parameters (e.g. distribution and orientation) in the concrete are not clear and uncontrolled (Park et al., 2012), which is negative for improve the fibre efficiency and the sustainability of UHPFRC development (Rossi, 2013). Based on available literature, some traditional methods (e.g. magnetic field) are used to control the fibre parameters (Torrents et al., 2012), but the obtained results are not satisfactory. Moreover, some researchers show that the flowing process of fresh concrete can be utilized to control the fibre parameters and further improve the concrete properties (Grünewald, 2004). However, compared to the normal concrete, UHPFRC is a much more complex system, which has high content of cementations materials, low water to binder ratio (W/B), and high content of superplasticizer, resulting in a large viscosity of concrete. Besides, the content of fibre in UHPFRC is much higher than normal reinforced concrete, reaching 2–3% by volume. Therefore, to promote an effective method that can control the distribution and orientation in UHPFRC cementitious system, some exploratory investigations have been done, and the effect of fibre orientation on the flexural (Yoo et al., 2016) and tensile strength (Bastien-Masse et al., 2016) of UHPFRC is studied. Nevertheless, there is still a need to systematical analyze the key controlling factors and fibre efficiency for a UHPFRC with optimized fibre parameters.

In general, based on these premises mentioned above, to promote the sustainable development of UHPFRC, its matrix and used fibres efficiencies should be optimized. Therefore, in this study, two strategies are mainly employed: 1) optimized design of the UHPFRC matrix based on modified Andreasen & Andersen particle packing model and appropriate application of substitutive materials; 2) efficient improve the fibre efficiency based on an optimized casting method. To systematically evaluate the contribution of each proposed method on a cleaner production for UHPFRC, the concept of embedded CO_2 emission is employed for further evaluation.

2. Materials and experimental methodology

2.1. Materials

The cement used in this study is Ordinary Portland Cement (52.5). A polycarboxylic ether based superplasticizer is used to adjust the workability of concrete. Several supplementary cementing materials (SCM), such as fly ash (FA), ground granulated blastfurnace slag (GGBS) and silica particles (S-P) in slurry, are used as pozzolanic materials to replace cement. Limestone powder (LP) is treated as filler in this study. Four types of sand are used: micro-sand, sand (0–0.6), sand (0.6–1.25) and sand (0–2). Additionally, one type of steel fibres is utilized: length = 13 mm,

Table 1
Materials types and densities.

Materials	Specific density (kg/m^3)	Pozzolanic activity index (28 days)
Cement	3150	–
FA	2293	83
GGBS	2893	96
LP	2710	–
Micro sand	2720	–
Sand (0–2)	2640	–
Sand (0–0.6)	2650	
Sand (0.6–1.25)	2645	
Superplasticizer	1050	–
Silica particles	2200	105
Steel fibres	7800	–

Table 2
Oxide composition of the used powder materials.

Substance	C (mass %)	FA (mass %)	GGBS (mass %)	LP (mass %)	S-P (mass %)
CaO	64.60	4.46	38.89	89.56	0.08
SiO_2	20.08	55.32	34.18	4.36	98.68
Al_2O_3	4.98	22.45	13.63	1.00	0.37
Fe_2O_3	3.24	8.52	0.51	1.60	–
K_2O	0.53	2.26	0.43	0.34	0.35
Na_2O	0.27	1.65	0.33	0.21	0.32
SO_3	3.13	1.39	1.41	–	–
MgO	1.98	1.89	10.62	1.01	–
TiO_2	0.30	1.17	–	0.06	0.01
Mn_3O_4	0.10	0.11	–	1.605	–
P_2O_5	0.74	0.76	–	0.241	0.15
Cl^-	0.05	0.02	–	–	0.04

(C: Cement, FA: Fly ash, GGBS: Ground granulated blast-furnace slag, LP: Limestone powder, S-P: Silica powder).

diameter = 0.2 mm. More detailed information and characteristics of the used materials are shown in Tables 1 and 2 and Fig. 2.

2.2. Experimental methodology

2.2.1. Mix design for a dense particle packing skeleton

To effectively develop a sustainable/eco-friendly UHPFRC, its skeleton should be dense and strong enough. Hence, in this study, the modified Andreasen and Andersen (A&A) model is utilized to design the concrete matrix, which is shown as follows (Funk and Dinger, 1994; Brouwers and Radix, 2005):

$$P(D) = \frac{D^q - D_{\min}^q}{D_{\max}^q - D_{\min}^q} \tag{1}$$

where D is the particle size (μm), P(D) is a fraction of the total solids being smaller than size D, $D_{\max}$ is the maximum particle size (μm), $D_{\min}$ is the minimum particle size (μm) and q is the distribution modulus.

As known that different types of concrete can be designed using Eq. (1) by applying different q values, since it determines the proportions (%) between the fine and coarse particles in the mixture. Considering the fact that a number of fine particles are utilized to produce the UHPFRC matrix, the value of q is fixed at 0.23 in this study, based on the recommendation by Hunger (2010). The mass proportions (%) of each individual material in the concrete mixture are adjusted until an optimum fit (smallest difference) between the composed mix and the target curve is reached, utilizing an algorithm based on the Least Squares Method (LSM), as shown in Eq. (2) (Hüsken, 2010).

$$RSS = \frac{\sum_{i=1}^{n}\left(P_{mix}\left(D_i^{i+1}\right) - P_{tar}\left(D_i^{i+1}\right)\right)^2}{n} \tag{2}$$

where P_{mix} is the composed mix, the P_{tar} is the target grading calculated from Eq. (1), and n is the number of points (between $D_{\min}$ and $D_{\max}$) used to calculate the deviation.

The quality of the resulting integral grading curve fit is assessed by the coefficient of determination (R^2, as shown in Eq. (3)), since it provides a value for the correlation between the grading of the target curve and the one represented composed mixture (Yu et al., 2016).

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(P_{mix}\left(D_i^{i+1}\right) - P_{tar}\left(D_i^{i+1}\right)\right)^2}{\sum_{i=1}^{n}\left(P_{mix}\left(D_i^{i+1} - \overline{P_{mix}}\right)^2\right.} \tag{3}$$

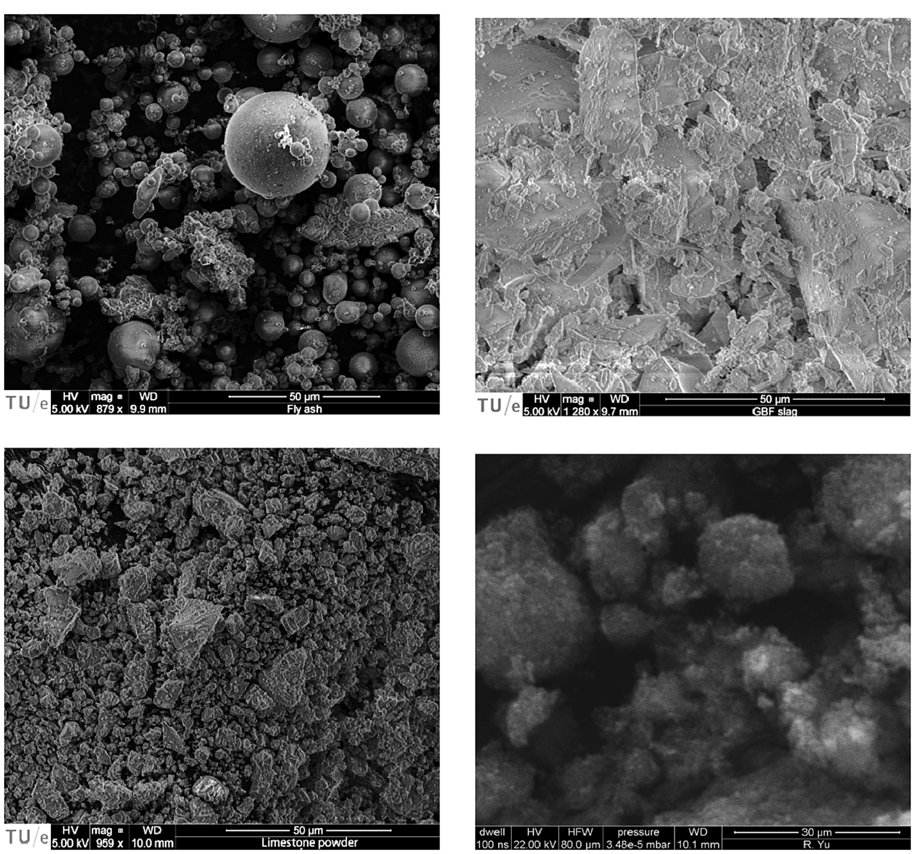


Fig. 2. SEM pictures of used Fly ash (a), Ground granulated blast-furnace slag (b), Limestone powder (c) and Silica particles (d).

Table 3
Mix recipes of the designed UHPFRC matrix (kg/m^3 concrete).

NO.	C (kg/m^3)	FA (kg/m^3)	GGBS (kg/m^3)	LP (kg/m^3)	S (kg/m^3)	MS (kg/m^3)	S-P (kg/m^3)	W (kg/m^3)	SP(kg/m^3)	W/B
1	591.9	264.3	0	0	1057.0	220.2	24.7	159.3	44.0	0.18
2	606.4	0	270.7	0	1082.9	225.6	25.3	163.2	45.1	0.18
3	602.8	0	0	269.1	1076.5	224.3	25.1	162.2	44.9	0.18$^{\#}$
Ref.	883.9	0	0	0	1091.2	227.3	25.5	164.4	45.5	0.18

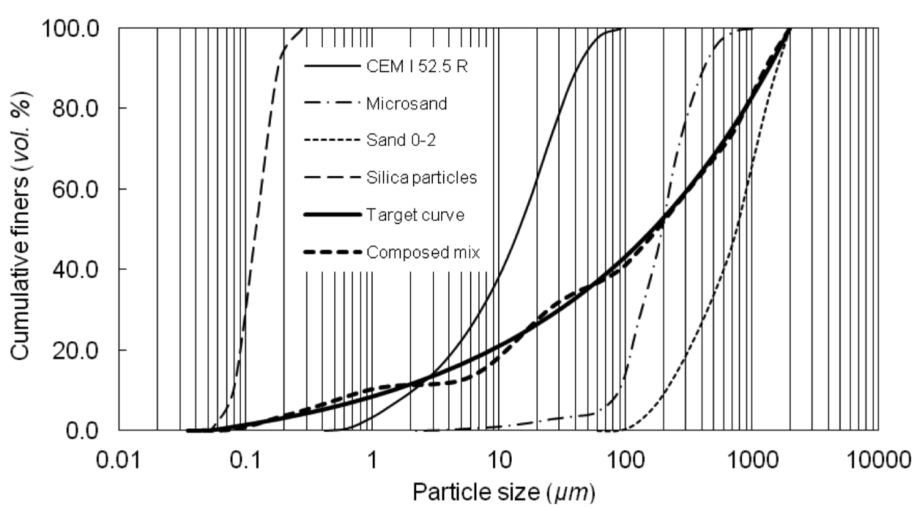
(C: Cement, FA: Fly ash, GGBS: Ground granulated blast-furnace slag, LP: Limestone powder, S: sand, MS: Microsand, S-P: Silica particle, W: Water, SP: Superplasticizer, W/B: water to binder ratio, Ref.: reference samples without industry by-products, #: LP is considered as a binder in the calculation).

Where $\overline{P_{mix}} = \frac{1}{n}\sum_{i=1}^{n} P_{mix}(D_i^{i+1})$, which represents the mean of the entire distribution.

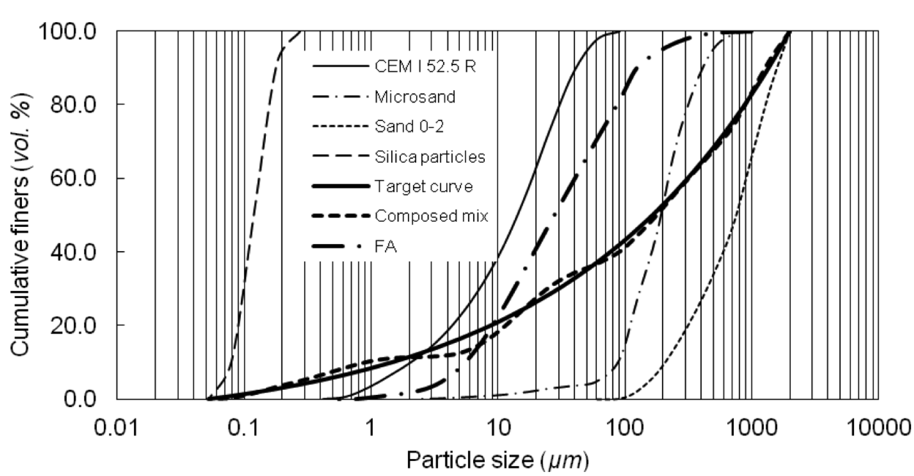
In this research, the developed UHPFRC matrix based on application of different substitutive industry by-products are listed in Table 3. Compared to the reference sample, about 30% of Portland cement (by mass) is replaced by FA, GGBS or LP in the mixtures. Two examples of the resulting integral grading curves are shown in Fig. 3 (due to the fact that the PSD of all the used substitutive materials are similar, only one example with fly ash is shown here). Additionally, to well control the fibre parameters in UHPFRC during the flowing process, the flowability of the developed UHPFRC mixture (with steel fibres) should be advanced. Hence, the developed recipe of UHPFRC (with fibres) is shown in Table 4.

2.2.2. Mixing and casting procedures

In this study, to guarantee an advanced properties of the developed UHPFRC, its mixing and casting procedures are shown as follows:



(a): Optimized UHPFRC matrix without industry by-products



(b): Optimized UHPFRC matrix with industry by-products (fly ash)

Fig. 3. PSDs of the involved ingredients, the target and optimized grading curves of the developed UHPFRC matrix: (a) without industry by-products; (b) with industry by-products (one example - fly ash).

Table 4
Mix recipes of the designed UHPFRC (with steel fibres)*.

C	FA	S-P	Sand (0–0.6)	Sand (0.6–1.25)	W	SP	SF (vol. %)
700	150	50	704	400	180	30	0–2.5

(C: Cement, FA: Fly ash, S-P: Silica particles, W: Water, SP: Superplasticizer, SF: Steel fibres (0, 0.5, 1, 1.5, 2, 2.5% by volume), *to guarantee a high flowability and acceptable mechanical properties for the designed UHPFRC, a new recipe is proposed also based on modified Andreasen and Andersen model).

1) All the powders and sands are added into a mixer for dry mixing (30 s at low speed);
2) Then, around 75% (by mass) of water is gradually added into the mixer. After 90 s mixing (low speed), the mixer is stopped for 30 s;
3) Afterwards, superplasticizer, steel fibres (if needed) and remaining water are added into the mixer for 180 s mixing at low speed;
4) Finally, a120 s mixing at high speed is executed.

After finishing the mixing, two different methods are used to cast the fresh UHPFRC (with fibres): 1) cast at one side of the mould (with flowing process, Fig. 4 (a)); 2) cast randomly (without flowing process, Fig. 4 (b)). For the UHPFRC matrix, the second casting method is chosen. In this study, the mixing and casting processes are always executed under laboratory conditions with dried and tempered aggregates and powder materials. The room temperature while mixing and testing is constant at around 21 °C.

2.2.3. Workability test

To assess the fresh behavior of the developed UHPFRC, EN 1015-3 (2007) is employed in this study. During the test, the cone is lifted straight upwards, and no jolting is executed. Then, two diameters perpendicular to each other are measured and recorded, and their mean is treated as the slump flow value of the designed UHPFRC (with steel fibres).

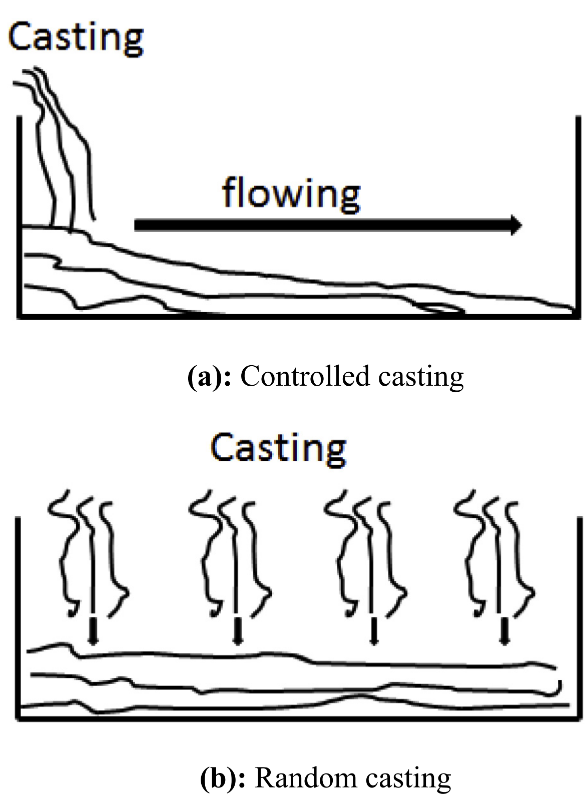


Fig. 4. Two cast methods that used in this study for UHPFRC production: (a): controlled casting with flowing process, (b) random casting without flowing process.

2.2.4. Mechanical properties test

All the fresh concrete is cast in moulds with the dimensions of 40 × 40 × 160 mm. The prisms are demoulded approximately 24 h after casting and then cured in water at about 21 °C. After certain curing days, the flexural and compressive strengths of the specimens are tested according to the standard - EN 196-1 (2005). At least three samples are measured at each age (for the calculation of average strength).

2.2.5. Calorimetry analysis

Following the recipes shown in Table 3, the pastes (without aggregates) are carefully produced for the calorimetry analysis. All the pastes are firstly mixed for about 2 min and then injected into a prepared ampoule, which is then placed into isothermal calorimeter (TAM Air, Thermometric). The inside temperature is controlled at 20 °C. After 7 days, the measurement is finished and the obtained data is analyzed. All results are checked and ensured by double measurements (parallel testing).

2.2.6. Image analysis

To evaluate the fibre orientation in UHPFRC mixtures, an image analysis tool is utilized in this study. Firstly, the hardened UHPFRC samples (40 mm × 40 mm × 160 mm) are cut into four pieces on average. Then, the cross section, which is called RGB image, can be converted into binary image by picture processing software (Yoo et al., 2016). The information of steel fibres on the cross section, including the number of steel fibres and the area of the steel fibres, can be obtained from the binary image. Based on the area of the steel fibres and the number of steel fibres in the binary image, the average diameter of fibres on the cross section can be obtained, as follows:

$$D_{aver} = \sqrt{\frac{4A}{\pi n_{number}}} \tag{4}$$

where D_{aver} is the average diameter of the steel fibres on the cross section; A is the area of steel fibres on the cross section; n_{number} is the number of steel fibres on the cross section.

It is clear that when the fibers are aligned along the length of the mould, the average fibre diameter on the cross section is the smallest, and the flexural strength of the concrete should be the highest. Therefore, when the D_{aver} value is the smallest, the fibres orientation in UHPFRC is the best.

3. Experimental results and discussion

3.1. Mechanical properties of the designed UHPFRC matrix (without fibres)

Fig. 5 presents the compressive strength of the designed UHPFRC matrix (without fibres) at 28 and 91 days. It can be noticed that the reference sample always has the highest compressive strengths at both 28 and 91 days, which can be attributed to its high cement content. As shown in Table 3, the cement content it about 884 kg/m^3 in the reference sample, which that about 30% of the cement is replaced by FA, GGBS and LP in the other mixtures. High cement amount implies more hydrated cement and hydration products, which is a guarantee for a higher mechanical property. When the cement is partly replaced by

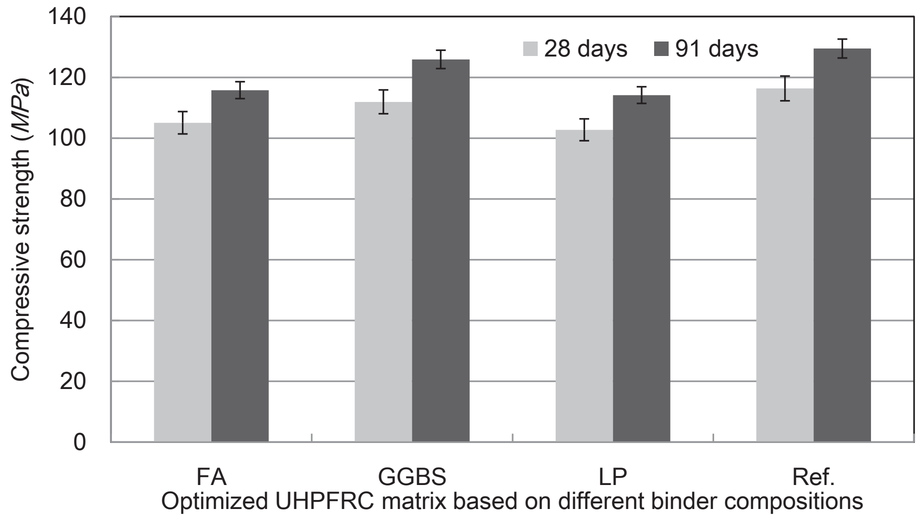


Fig. 5. Compressive strengths of the designed UHPFRC matrix with different mineral admixtures.

industry by-products, it can be found here the mixture with GGBS has superior mechanical properties at both 28 and 91 day, while that the strengths of the mixtures with FA or LP are similar to each other. This observation is not in a line with the results obtained for normal strength concrete (Hwang and Shen, 1991). In most cases, the pozzolanic reaction of FA begins at the age of 3 days after blending with cement and water, while its pozzolanic reaction is much slower than the Portland cement hydration. Therefore, after curing for 28 days, a very limited amount of C-S-H gel can be generated from FA, and the microstructure of the concrete is less dense than the one with GGBS. Nevertheless, with an ongoing cement hydration, more portlandite can be generated and the pozzolanic reaction of FA can be accelerated, which causes that the already formed pore structure in concrete is filled by the new generated C-S-H and the mechanical properties of concrete are significantly improved after curing for 91 days. However, in this research, the strengths of the mixture with FA are similar to that of the mixture with LP after curing for 91 days, which means that the pozzolanic reaction of FA can not proceed well in the cementitious system of UHPFRC matrix.

According to the compressive strength results obtained in this study, it can be summarized that based on appropriate application of modified Andreasen and Andersen particle packing model, a dense packed UHPFRC matrix skeleton can be obtained. It binder efficiency is higher than that shown in available literature (as shown in Table 5). When the unhydrated cement particles in this dense packed skeleton are replaced by industry by-products, the utilized cement amount can be reduced by about 30%, and the concrete mechanical properties are still acceptable.

3.2. Hydration kinetics of the designed UHPFRC cementitious system

Fig. 6 illustrates the calorimetry test results for the designed UHPFRC matrix cementitious system. It can be noticed that the dormant period, relative setting time, as well as the time to reach the maximum hydration peak for the mixture with FA, GGBS or LP are similar to each other at the initial hydration process, and the hydration speed for the reference sample is the highest. These phenomena mentioned above can be attributed to the following reasons: 1) A large amount of superplasticizer is utilized in the production of the UHPFRC cementitious system. Based on the investigation of Jansen et al. (2012), complex Ca^{2+} ions from pore solution by the superplasticizer should be the substance that can absorb the polymer on the nuclei or the anhydrous grain surfaces, which in turn might lead to prevention of the nuclei growth or to the dissolution of the anhydrous grains. Hence, in this study, the pozzolanic reaction of FA and GGBS is restricted during the initial hydration process. 2) Low water content is used in the UHPFRC matrix production. The high powder amount and low water content can cause that much water is absorbed by the powder materials and limited free water stay in the cementitious system, which directly result in that the diffusion of Ca^{2+} and OH^- is restricted, and pozzolanic reaction of FA or GGBS is simultaneously postponed. Additionally, the normalized (by 1 g of cement) total heat of the developed UHPFRC matrixes demonstrate that the cement hydration efficiency is the lowest and the hydration of the mixture with GGBS can be better promoted in the later age than that with FA or LP. Hence, based on the results of calorimetry test, to effectively

Table 5
Comparison of the binder efficiency (B_e) for the matrix optimized and non-optimized UHPFRC.

References	Binders (kg/m^3)		Water/binder ratio	Fibre (vol. %)	f_c (MPa)	B_e (%)
	C	S				
Yang et al. (2009)	950	238	0.2	2	190	15.99
Toledo Filho et al. (2012)	1011	58	0.15	2	160	14.97
Corinaldesi (2012)	960	240	0.16	2.5	155	12.92
This study	884	26	0.18	2.5	156	17.14

(C: Cement, S: Silica particle, f_c: compressive strength at 28 days, B_e: binder efficiency (as shown in the literature (Yu et al., 2014)).

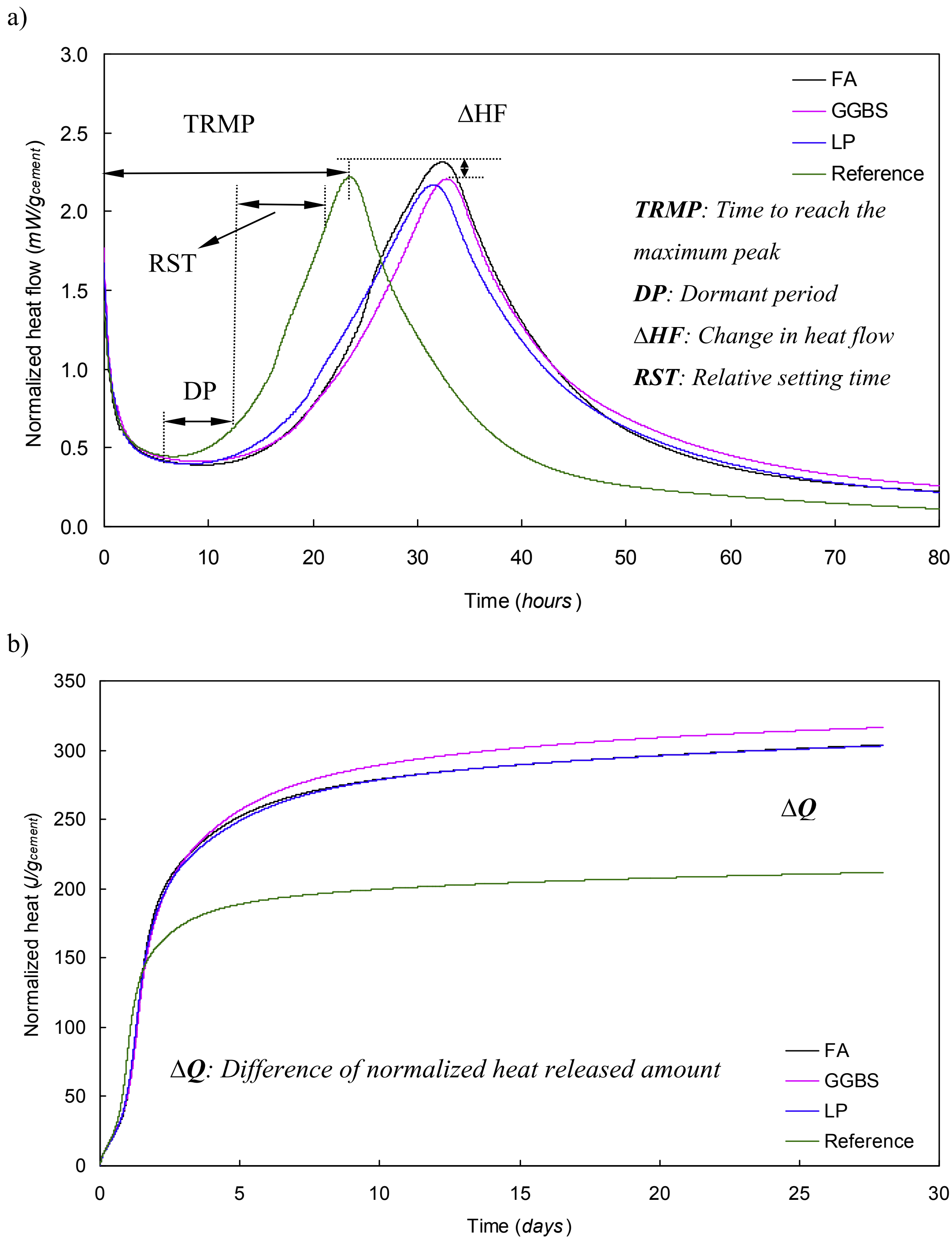


Fig. 6. Calorimetry test results of UHPC pastes with different mineral admixtures: a) normalized heat flow, b) normalized total heat.

replace the cement in UHPFRC by industry by-products, a sufficient hydration time (in normal curing condition) should be guaranteed.

3.3. Ecological evaluation of the designed UHPFRC matrix (without fibres)

To evaluate the eco properties of the designed UHPFRC matrix (without fibres), the concept of embedded CO_2 emission is employed in this study, which focus on the amount of materials required for 1 m^3 of compacted concrete. Based on the embodied CO_2 values for each components of concrete (Randl et al., 2014), the embedded CO_2 emissions of the designed UHPFRC matrix in this study are calculated and shown in Fig. 7. It is obvious that the reference sample has the highest embedded CO_2 emission, while that value for the mixture with industry by-products are much lower (about 30% less) and similar to each other. This can be

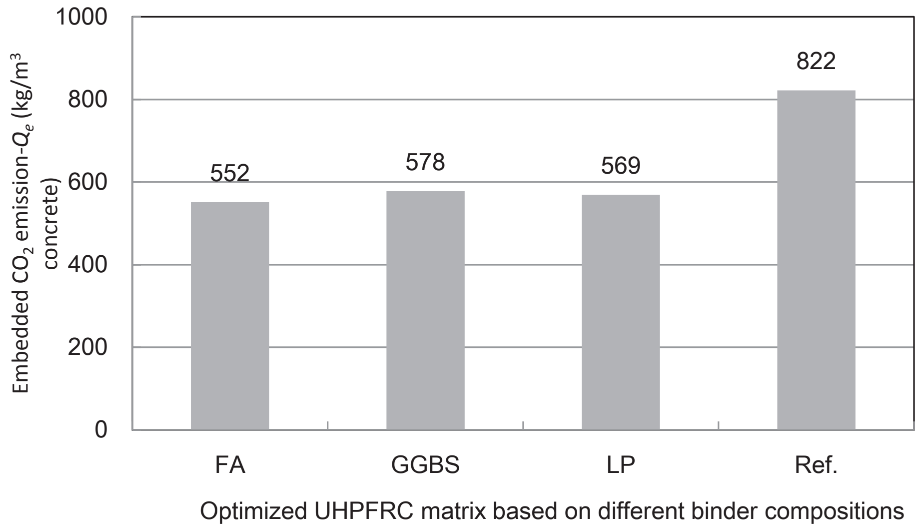


Fig. 7. Comparison of embedded CO_2 emission (Q_e) for the optimized UHPFRC matrix based on different binder compositions.

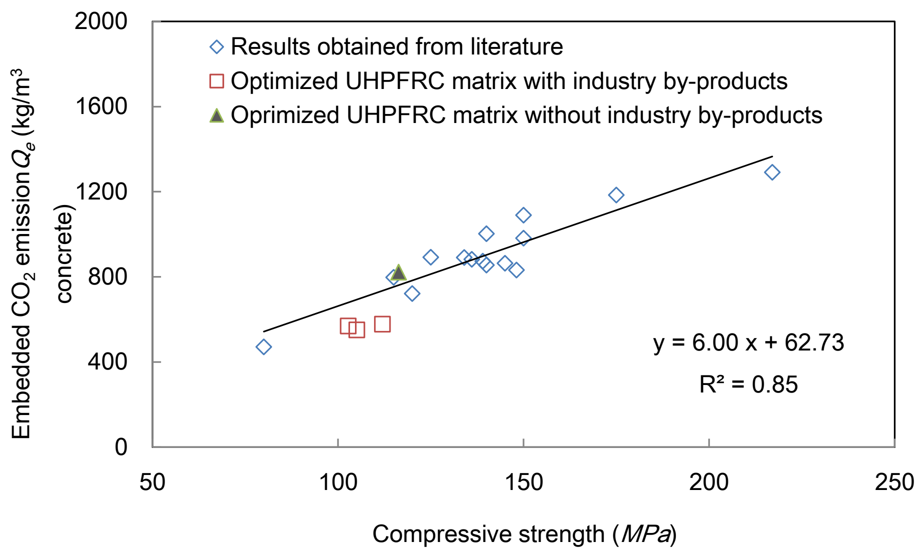


Fig. 8. Comparison of embedded CO_2 emission for the optimized UHPFRC matrix with and without industry by-products and that obtained from available literature.

attributed to the large cement amount in reference sample and the relatively high environmental impact of cement material. Therefore, appropriately replace the cement by industry by-products is a promising method to promote the sustainable development of UHPFRC. To further demonstrate that the particle packing model and the substitutive materials can effectively reduce the UHPFRC environmental impact without sacrificing its superior mechanical properties, a comparison of the relationship between embedded CO_2 emission and compressive strength for the designed UHPFRC matrix and other UHPFRC obtained in literature is presented in Fig. 8. It can be noticed that the enhancement of compressive strength of all the analyzed UHPFRC corresponds to an increase of the embedded CO_2 emission and environmental impact, and this increasing trend is almost linear. Moreover, the point representing the reference sample (without industry by-products) is more or less on the trend line, which implies that the design of UHPFRC matrix only based on particle packing model without applying substitutive materials is ineffective in reducing its environmental impact. When the industry by-products (especially the GGBS) are utilized together with particle packing model, the environmental impact of the designed UHPFRC matrix can be obviously decreased without sacrificing its compressive strength.

3.4. Fresh behavior of the optimized UHPFRC (with fibres)

For the sustainable development of UHPFRC, the used steel fibres are also very important. As mentioned before, the concrete flowing process is a promising method to control the fibre parameters and improve fibre efficiency. Hence, to achieve this goal, the designed UHPFRC should be flowable. The flowability of the optimized UHPFRC in this study is shown in Fig. 9. It is clear that with an increase of the added steel fibres, the flowability of UHPFRC gradually decreases until the steel fibre amount is 2% (vol.). When the added steel fibres is about 2.5%, there is a sharply decrease of the UHPFRC flowability (to about 283 mm). The phenomenon observed above may be caused by the network structure formed by the cross-over of steel fibre in fresh concrete, which can increases the resistance of fresh UHPFRC flow (Boulekbache et al., 2014). In

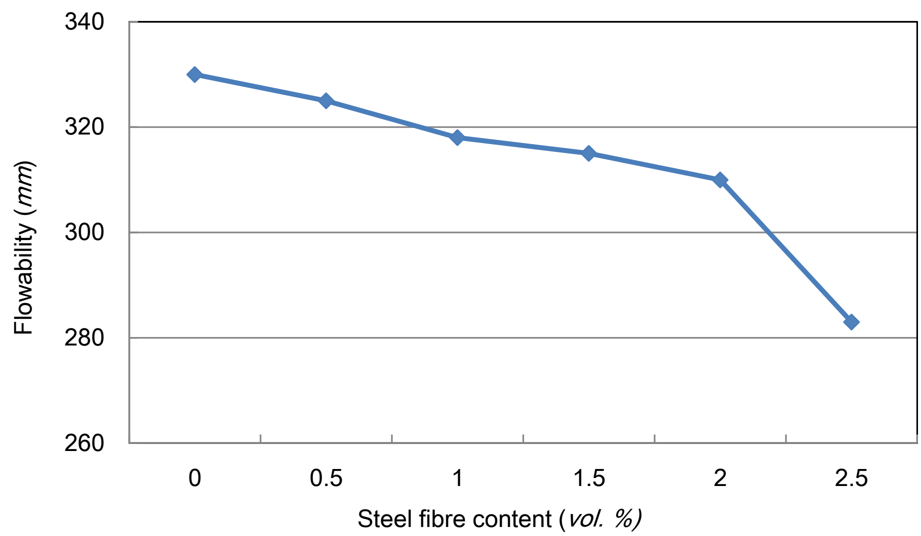


Fig. 9. The flowability of the optimized UHPFRC with different steel fibre content.

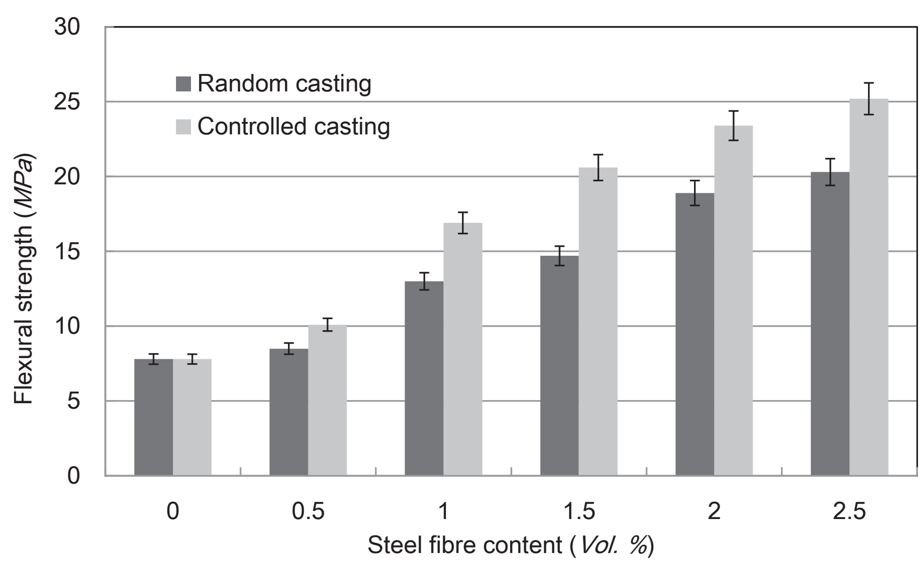


Fig. 10. Comparison of the flexural strengths for the designed UHPFRC with different casting methods.

general, the designed UHPFRC has relatively high flowability, which is a premise to control the fibre parameters in fresh UHPFRC. To guarantee that the optimized UHPFRC has both high flowability and acceptable mechanical properties, the mixture with 2% (vol.) steel fibres (slump flow is about 310 mm) is chosen to continue the following experiments.

3.5. *Mechanical properties of the optimized UHPFRC and fibre efficiency*

As commonly known, the mechanical properties of concrete (especially the flexural strength) has close relationship with the fibre orientation. In this study, two casting methods are employed to understand the effect of fibre orientation on UHPFRC flexural strength and fibre efficiency. Fig. 10 illustrates the flexural strengths of the designed UHPFRCs with different fibre contents and casting methods. The two curves represent the flexural strength of UHPFRC that cast at one side of the mould (with flowing process, namely controlled casting) and cast randomly (without flowing process, namely random casting). It is clear that the flexural strength of the UHPFRC cast at one side of the mould is always higher than that of UHPFRC cast randomly, which is similar as the results shown by Yoo et al. (2016). This can be attributed to the influence of fibre orientation in UHPFRC. When a large amount of steel fibres are perpendicular to the flexural force direction, the steel fibres can significantly resistant the cracks generation and growth, which is helpful for improving the concrete flexural strength. This also demonstrates that the flowing direction is one of the important factors to control the fibre orientation in UHPFRC.

To clearly understand the improvement of fibre efficiency in the UHPFRC produced by controlled casting method, the steel fibre efficiency of the designed UHPFRC in this study is calculated based on the equation as follows:

$$K_f = \frac{(f_1 - f_0)}{n_0} \tag{5}$$

where K_f is the fibre efficiency, f_1 is the flexural strength of designed UHPFRC with different steel fibre content, f_0 is the flexural strength of the reference sample without fibres, n_0 is the steel fibres content

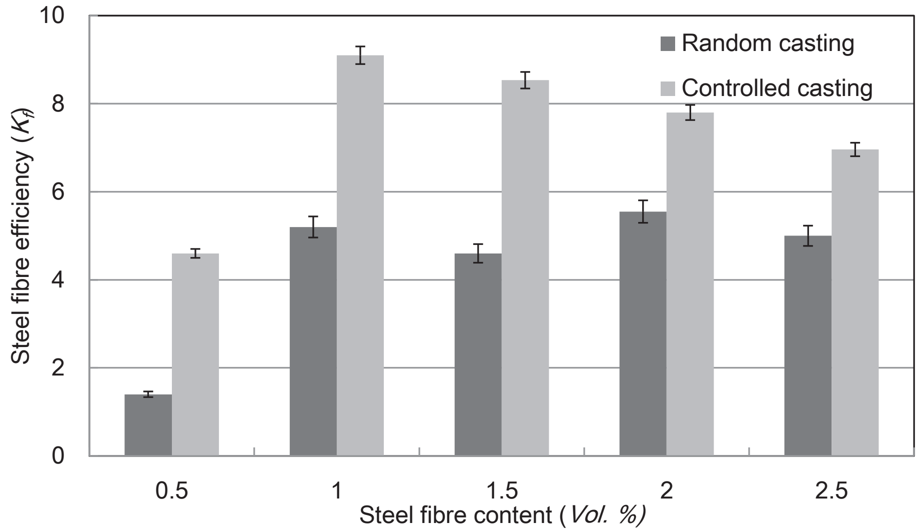


Fig. 11. Comparison of steel fibre efficiency (K_f) of the designed UHPFRC based on different casting methods.

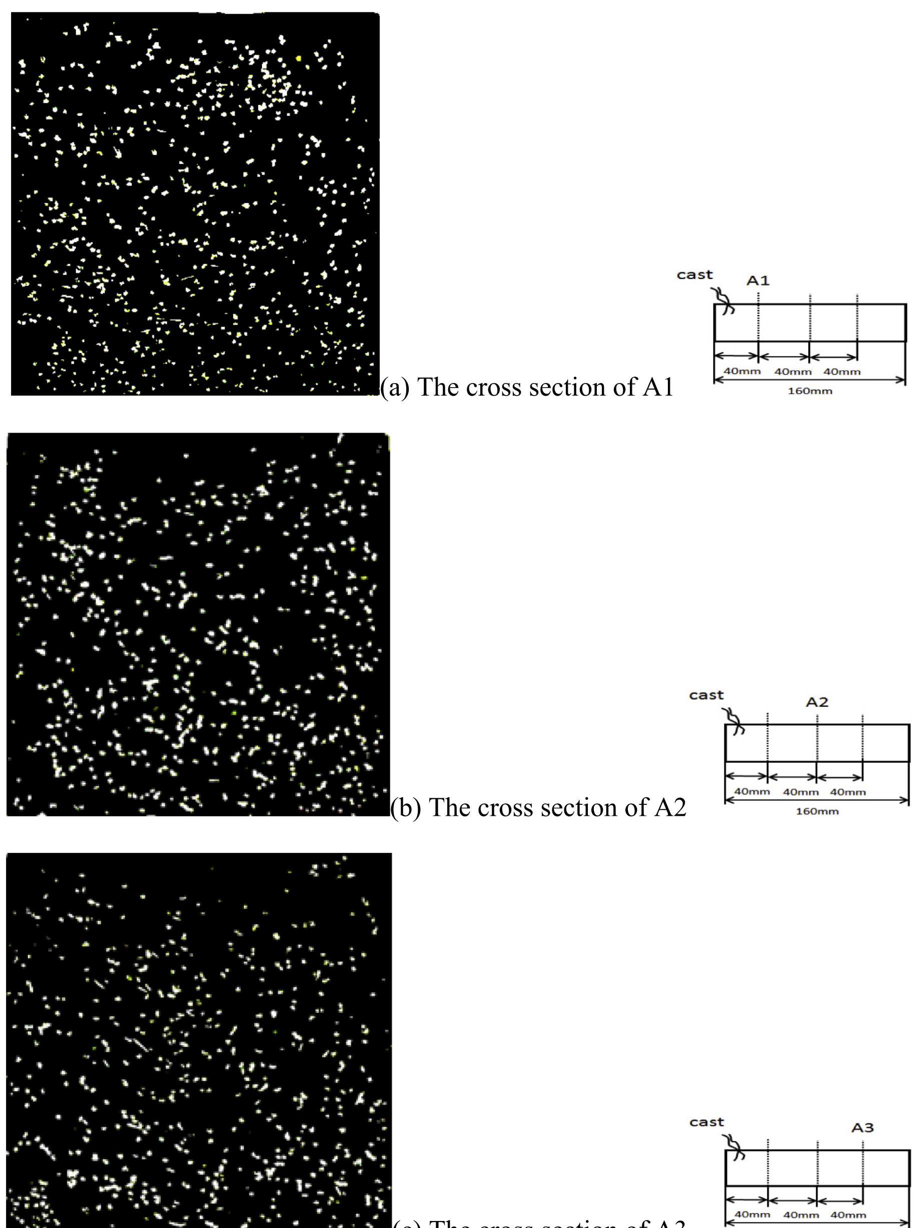


Fig. 12. The cross section of hardened UHPFRC based on controlled casting method (cast at one side of the mould with 2% fibre vol.).

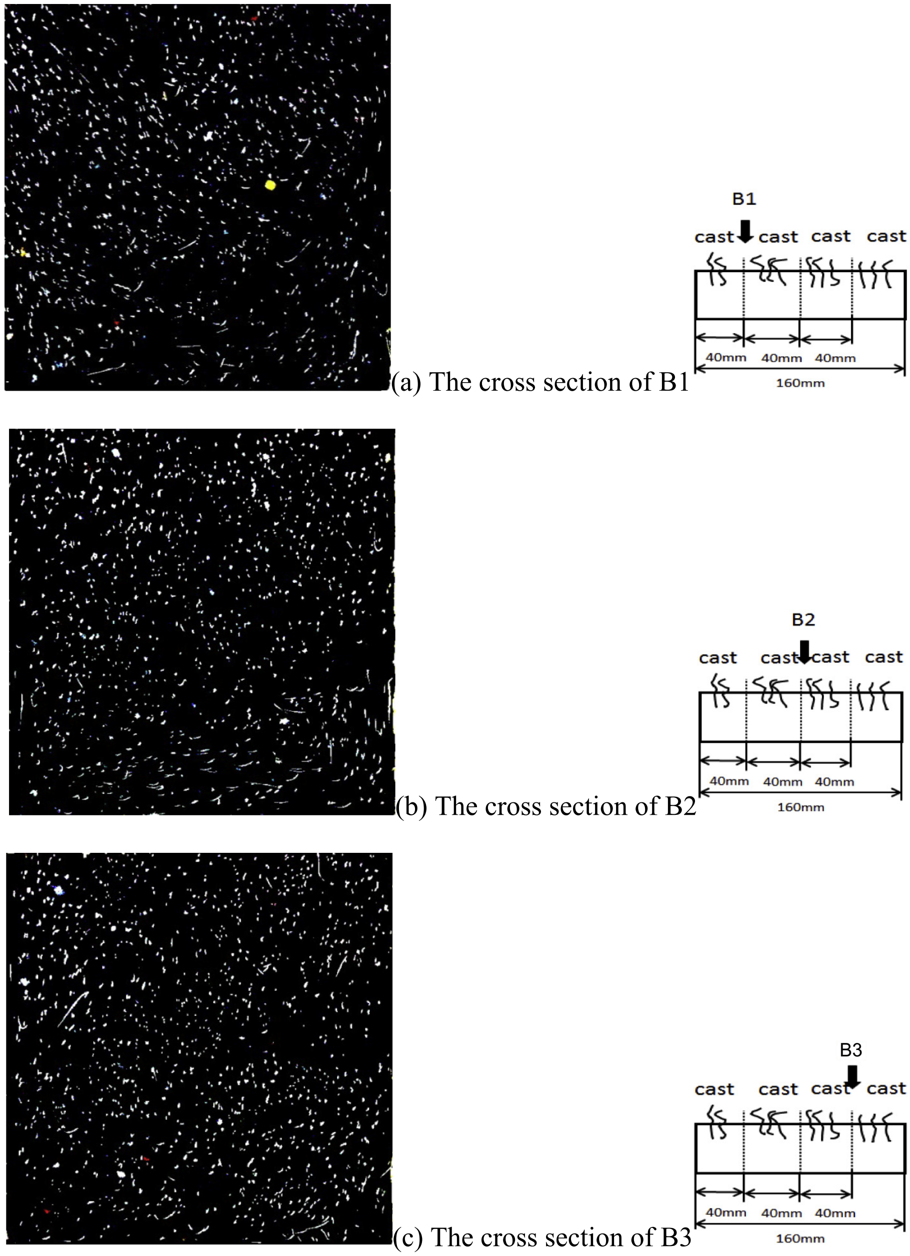


Fig. 13. The cross section of hardened UHPFRC based on random casting method (cast randomly with 2% fibre vol.).

(vol.).

As shown in Fig. 11, with an increase of the steel fibre content, the fibre efficiencies of all the UHPFRCs based on different casting methods firstly increase sharply. Then, for the UHPFRC based on controlled casting method, its fibre efficiency decrease gradually, while that for the random casting sample fluctuate by about 10%. Moreover, it is clear that the fibre efficiencies of the samples based on controlled casting method is much higher than that based on random casting (about 50% more). This further demonstrates that the controlled casting method can effectively control the fibre orientation can improve the fibre efficiency of UHPFRC.

3.6. *Effect of casting methods on the fibre orientation in UHPFRC*

To further understand the effect of different casting methods on the fibre orientation of the designed UHPFRC in this study, the UHPFRC sample (40 mm × 40 mm × 160 mm) is cut into four pieces (40 mm × 40 mm × 40 mm) on average and an image analysis tool is used to analysis the cross section. Figs. 12 and 13 show the fibre orientation of UHPFRC that cast at one side of the mould (with flowing process) and that cast randomly (without flowing process), respectively. Based on the calculation method (Eq. (4)), it can be found that the D_{aver} (average fibre diameter) for the controlled casting sample has a tendency to decrease firstly and then rise during the flowing process, which implies that at the middle place of UHPFRC based on controlled casting most fibres are aligned along the length of the mould. This also explains the high flexural strength for the UHPFRC sample based on controlled casting method, since the aligned steel fibres can more effectively resist the cracks generation and growth. But, at the beginning and the end of the fresh UHPFRC flowing process, the fibre orientation is relatively disordered, which can be attributed to the wall-effect.

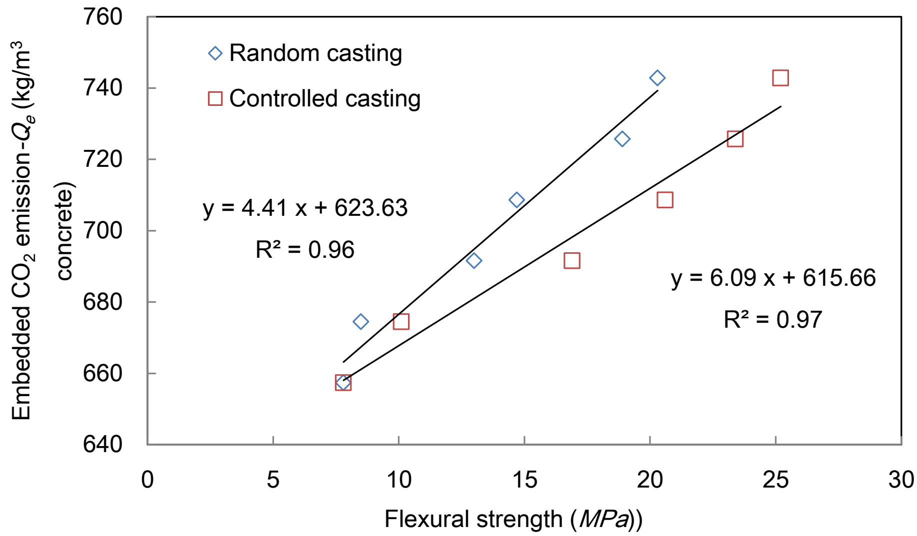


Fig. 14. Comparison of embedded CO_2 emission (Q_e) for the designed UHPFRC based on different casting methods.

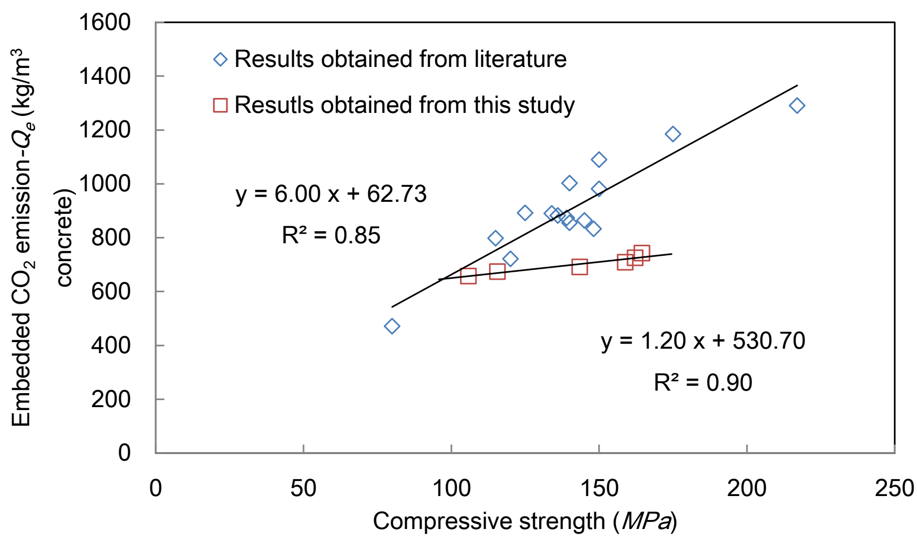


Fig. 15. Variation of embedded CO_2 emission of the optimized UHPFRC and other UHPFRCs presented in available literature with an increase of concrete compressive strengths at 28 days.

In general, based on all the obtained experimental results, it can be summarized that the flowing process of UHPFRC can be utilized to control the fibre orientation and improve the fibre efficiency. The flowing process can be separated into disorder period, stable period and re-disorder period. Hence, to further improve the fibre efficiency and optimized fibre orientation, the wall-effect should be well controlled.

3.7. Ecological evaluation of the optimized UHPFRC (with fibres)

As shown in previous sections, the concept of embedded CO_2 emission is also employed to evaluate the eco properties of the optimized UHPFRC based on different casting methods (as presented in Fig. 14). It is obvious that with almost the sample flexural strength, the designed UHPFRC based on controlled casting method presents low environmental impact. For instance, when the flexural strength is about 20 MPa, the embedded CO_2 emissions are about 700 and 750 kg/m^3 for the UHPFRC based on controlled casting and random casting. This further demonstrates the controlled casting method can effectively promote the sustainable development of UHPFRC for a cleaner production.

When particle packing model, substitutive materials and controlled casting method are utilized together, the optimized UHPFRC show much lower environmental impact than that obtained from available literature, which can be proved by Fig. 15. For example, when the compressive strength is about 160 MPa, the embedded CO_2 emission of the optimized UHPFRC in this study is about 730 kg/m^3, while that for normal UHPFRC from literature is more than 1000 kg/m^3. Therefore, to effectively promote the sustainable development of UHPFRC, packing model, substitutive materials and controlled casting method should be well assembled together.

4. Conclusions

This paper presents a cleaner production approach for Ultra-

High Performance Fibre Reinforced Concrete (UHPFRC). In general, two strategies based on theoretical and practical points of views are employed here: 1) optimized design of the UHPFRC matrix based on modified Andreasen & Andersen particle packing model and appropriate application of substitutive materials; 2) efficient improve the fibre efficiency based on an optimized casting method. From the results presented in this paper the following conclusions are drawn:

- Based on appropriate application of modified Andreasen and Andersen (A&A) particle packing model, a dense packed UHPFRC matrix skeleton can be obtained, which has relatively higher binder efficiency. Due to the fact that the added industry by-products can be treated as the particles that replaced the unhydrated cement particles in the dense packed skeleton, the mechanical properties of UHPFRC (with about 30% less cement) are still acceptable, and its environmental impact can be reduced by about 30%.
- The hydration kinetics of the designed UHPFRC matrix with FA, GGBS and LP are similar to each other during the initial five days. Afterwards, the hydration rate of the mixture with GGBS is obviously accelerated. Therefore, to effectively replace the unhydrated cement in UHPFRC by industry by-products, a sufficient hydration time (in normal curing condition) should be guaranteed. This can significantly improve the materials efficiencies in the UHPFRC production.
- Based on the control of the flowing parameters (e.g. flowing direction) for the fresh UHPFRC, the fibre orientation can be controlled, which guarantee that most fibres are aligned along the length of the mould at the middle place of UHPFRC. Hence, during the flexural testing, the aligned steel fibres can well resist the growth of cracks and improve the mechanical properties of the optimized UHPFRC. Additionally, the flowing process can be separated into disorder period, stable period and re-disorder period. Based on the practically control of the casting method, the steel fibre efficiency of UHPFRC can be effectively enhanced and the production of UHPFRC is more sustainable and cleaner.
- In this study, when the particle packing model, substitutive materials and controlled casting method are well utilized together, an optimized UHPFRC can be produced, which shows much lower environmental impact than that of normal UHPFRC obtained from available literature (about 30% less). The proposed new approach can further promote the development and application of UHPFRC, and contribute some new ideas for a cleaner production of cement based materials in the near future.

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List of symbols

A	Area of steel fibres on the cross section, mm^2
B_e	Binder efficiency, %
D	Particle size, μm
D_{aver}	Average diameter of the steel fibres on the cross section, mm
$D_{\max}$	Maximum particle size, μm
$D_{\min}$	Minimum particle size, μm
f_0	Flexural strength of the reference sample without fibres, MPa
f_1	Flexural strength of designed UHPFRC with different steel fibre content, MPa
K_f	Fibre efficiency, −
n_{number}	Number of steel fibres on the cross section, −
n_0	Steel fibres content (vol.), %
P_{mix}	Composed mix, −
P_{tar}	Target curve, −
$P(D)$	A fraction of the total solids being smaller than size D, −
Q_e	Embedded CO_2 emission kg/m^3 concrete
Q	Distribution modulus, −
RSS	Sum of the squares of the residuals, −

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