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Development of economic, practical and green ultra-high performance fiber reinforced concrete verified by particle packing model

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ABSTRACT

Ultra High Performance Fiber Reinforced Concrete (UHPFRC) is a type of concrete which possess very high compressive strength (more than 150 MPa) and high ductility which makes it a suitable material for manufacturing pre-cast structural elements. Manufacturing this type of concrete in large-scale is however not appealing to industry which leads to limited application. The main reason for this can be attributed to the manufacturing cost of UHPC due to the high cementitious materials and fine aggregate (less than 600 μm) contents. This study focused on a step by step procedure making UHPFRC more practical, cost-effective and green by not only introducing coarse aggregate in the mix but also increasing the aggregate content, resulting in lower consumption of cementitious materials. The particle packing of the mix design developments were compared to the modified Andreasen & Andersen particle packing model and it was confirmed that an increase in cement content can result in a reduction in strength when the combined particle size distribution contains too many particles of a similar size. The final proposed mix designs per compressive strength generates 10 % less CO_2 and 75 % more affordable than the typical commercial UHPFRC.

1. Introduction

Ultra High Performance Concrete (UHPC) Reinforced with Fiber, which known as (UHPFRC), is an ultra-high strength concrete with superior mechanical properties [1–8]. The high compressive strength (more than 150 MPa) and high ductility make UHPFRC a suitable material for manufacturing pre-cast structural elements. However, application is limited by cost as a result of the high cementitious materials and fine aggregate (less than 600 μm) contents.

The basic principles of ultra-high strength concrete with ductile behaviour, known as Reactive Powder Concrete (RPC), were suggested by Richard and Cheyrezy [9]. Eliminating the coarse aggregate to increase the homogeneity of the mix was one of their suggestions. In their proposed mix design, the ratio of sand to cement (by weight) was 1.1 and 600 μm was considered as the maximum size of aggregate. Cement and silica fume are the major cementitious materials. A mean compressive strength of 218 MPa was achieved through heat treatment at 90 °C (without any pre-setting pressurization). In order to get ultra-high strength (about 800 MPa), steel aggregate finer than 800 μm as well as heat treatment at 250–400 °C

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Nomenclature

D	Particle size (μm)
$P(D)$	Fraction of the total solids being smaller than size D
P_{mix}	Composed mix,
P_{tar}	Target curve
D_{max}	The maximum particle size (μm)
D_{min}	The minimum particle size (μm)
q	The distribution modulus
RSS	Sum of the squares of the residuals

and compacting pressure of 50 MPa were applied. They also managed to get compressive strengths between 490 MPa and 680 MPa by using heat treatment (at 250 °C–400 °C) and compacting pressure (of 50 MPa). Although numerous studies [2,3,10–15] investigated the behaviour of UHPC and UHPFRC following Richard and Cheyrezy's proposed principles, in large-scale application, this type of concrete is not very appealing for industry.

The composition of a typical commercial UHPFRC [6,15] widely used in literature [7,16,17] is listed in Table 1. This typical commercial UHPFRC has the following characteristics and associated disadvantages:

- **High content of cement:** Results in higher cost of the concrete, as well as higher shrinkage [18–20] and high emission of carbon dioxide [21,22].
- **High Silica fume content:** Silica fume can work as a cementitious material [23–25], while also increasing the packing density of concrete. However, this material is one of the most expensive materials in the mix design and from an economic perspective it should be minimized.
- **Low aggregate content:** In this commercial mix, the ratio of aggregate to cement (Agg/c) by weight is mostly kept at 1.1. The relatively low aggregate content leads to higher cost of final product as aggregate is normally a cheaper material in comparison to the other materials used in manufacturing concrete.
- **Utilizing fine aggregate**: Using very fine aggregate (less than 600 μm) is another characteristic of UHPFRC which usually impose extra cost to final products. It is noteworthy that in some UHPFRC mixes different gradings of aggregates are utilized, which adds preparation costs due to the sieving processes.

All these material requirements make UHPFRC unappealing, too expensive and less green for use in large-scale projects such as bridges and high-rise buildings. Further costs are incurred when it is not possible to obtain the required materials locally and materials have to be imported.

To overcome the discussed shortcomings of UHPFRC including eco-friendliness with less associated cost and energy consumption of this type of concretes, some studies investigated the effect of increasing aggregate content and size [26–32] while some others also considered the effect of different types of binder in the mixtures [5,28,33–36]. Considering coarser aggregate sizes in the mentioned literature include considering coarser aggregate up to 0.8 mm [26–29], 1 mm [30] and up to 4 mm [31,27–32] while other researchers considered binders effects along with the effect of aggregates. Yang et al. [5] achieved a compressive strength of 120 MPa (water cured in 20 °C) and about 180 MPa in 90 °C heat curing by using local

Table 1
Materials, mix design and properties of commercial UHPFRC [6,15].

Material	Amount (kg/m^3)
Portland cement	712
Fine sand	1020
Silica fume	231
Ground quartz	211
Superplasticizer	30.7
Accelerator	30
Steel fiber	156
Water	109
Reported properties	Amount
Compressive strength	180–225 MPa
Flexural strength	40–50 MPa
Modulus of elasticity	55–58.5 GPa
Entrapped void content	2–4%

Table 2
UHPC and UHPFRC mix designs in the literature.

Considerations	28-day compressive strength (MPa)	Fibers	Superplasticizer	Aggregate (>1 mm)	Aggregate (< = 1 mm)	Lime stone	Metakaolin	Glass powder	Silica flour	Fly ash	GGBFS	Silica fume	Water	Cement	Reference
• 4 aggregate types with sizes ranging from 0.15 mm -5 mm Sample water cured in 90 °C	**180**	–	13	105	945	–	–	–	–	–	430	119	181	657	[5]
• 2 aggregate size ranging 0.2- 0.8 mm Sample water cured in 20 °C	**250**	244	10	–	830	–	–	226	–	–	–	226	171	902	[26–27]
• 2 aggregate types with size ranging 0.15 mm - 0.53 mm • One out of 6 reported mix designs Sample water cured in 23 °C	**152**	141	9	564	246	–	–	–	–	146	–	199	175	795	[28]
• 2 aggregate types with median size ranging from 0.15 mm - 0.54 mm • one out of 18 reported mix designs Sample water cured in 23 °C	**165**	71	6	–	780	–	–	–	195	–	390	195	179	390	[29]
• One aggregate type size <1 mm used • One out of 5 reported mix designs Sample heat treated for 2 days in 90 °C	**180**	80	40	–	1100	–	–	–	–	–	–	149	151	742	[30]
• One aggregate type with four sizes ranging from 0.1 mm - 4 mm • one out of 8 reported mix designs Sample water cured	**120**	–	30	159	781	–	–	–	148	–	–	148	170	650	[32]
• One aggregate type with size of 0.95 mm • One out of 5 reported mix designs Sample water cured	**95**	–	11	–	1107	332	166	–	–	–	–	–	220	609	[33]
• One aggregate size ranging from 0.9 mm - 2 mm No curing regime was reported	**145**	–	–	–	977	–	–	–	178	89	–	178	208	889	[34]
• 1 aggregate type with different sizes (up to 3.0 mm) • One out of 14 reported mix designs Sample autoclaved at 210 °C	**281**	234	35	521	520	–	–	–	–	83	83	205	151	664	[35]
• 3 aggregate types with 5 median sizes ranging from0.15 mm- 3.38 mm • One out of 7 reported mix designs	**159**	131	6	551	499	–	–	–	89	–	–	116	142	646	[35]

Sample water cured in 23 °C

natural sand sized less than 5 mm and Ground Granulated Blast Furnace Slag (GGBS) as well as Silica Fume (SF) as supplementary cementitious materials. Pyo and Kim [28] studied the possibility of incorporating coal bottom ash and GGBSwith different particle sizes for enhancing material properties of UHPFRC. The median aggregate sizes and contents were limited to 0.15−0.53 mm and 1.02 (to cement by weight), respectively. Mo et al. [33] investigated the mechanical properties of UHPFRC containing limestone and different substitution percentage of metakaolin while the aggregate size was limited to the maximum particle diameter of 0.95 mm. 28-day compressive strength for all the studied mixes was lower than 100 MPa when the specimens were stored in 20 °C water. The highest 28-day compressive strength of 158 MPa was obtained. In the study conducted on UHPFRC by Qiu et al. [34] silica fume and fly ash were incorporated as supplementary cementitious materials and quartz sand as an only aggregate ranging from 0.9 mm to 2.0 mm with 1.1 content ratio to cement by weight. Yazici et al. [35] concluded that in order to get ultra-high strength in RPC there is no need to only use fine aggregate. They managed to get a strength of 281 MPa by autoclaving at 210 °C under 2 MPa pressure. The maximum aggregate size was 3 mm. The possibility of utilizing Fly Ash (FA) and GGBS as a silica source was investigated. Pyo et al. [36] investigated the mechanical properties of UHPFRC with coarser aggregates. They incorporated different types and sizes of aggregate in seven different UHPFRC mixtures. The aggregates included silica sands, dolomite and basalt ranging from 0.01 to 1.1 mm, 0.15–5 mm and 0.45–5.2 mm. the aggregate to cement ratio by weight was limited to 1.65. Cement and undensified silica fume were the only cementitious materials incorporated in the mix designs. The 28-day compressive strength achieved ranged from 130 to 161 MPa with no heat treatment. A summary of the abovementioned discussions on various mix designs and compressive strength are listed in Table 2.

Although these studies significantly improved the manufacturing process of UHPFRC without sacrificing their mechanical properties, their effort could still be improved from the economic and eco-friendliness to make UHPFRC more appealing to industry.

The aim of this study is the development of a practical, economic and green UHPFRC mixture with excellent UHPFRC properties which can compete with typical commercial UHPFRCs. In that regards, the following considerations were taken as manufacturing objectives:

- Cement content reduction of mixtures by increasing the aggregate content as a cost effective and green approach toward the reduction of CO_2 emission;
- Using coarser aggregate to reduce the manufacturing cost;
- Minimizing the utilization of expensive materials e.g. Silica fume and steel fiber, to reduce the final manufacturing costs
- Eliminating the milling and special mixers in the mixing process to reduce the manufacturing cost and improve its practicality
- Eliminating expensive curing methods e.g. autoclaving to reduce the cost and improve the practicality of the final product;
- Minimizing the sieving process. The eventual objective was using aggregate as supplied from query with no sieving as a cost effective approach of the final product;
- Utilizing only standard concrete laboratory equipment during manufacturing process as an effective approach toward the practicality of the final product.
- Using locally available materials in the South Africa market as a cost effective approach

The above-mentioned restrictions not only reduce the transportation, manufacturing, and associated energy costs of the final product but also make more eco-friendly concrete (less CO_2) with practical perspectives for commercial manufacturing of UHPFRCs.

As a part of achieving the favourable mix design, the materials used in the procedure are introduced step by step which led to the final mix design. In this phase of study, the effect of different materials on compressive strength of the mixture is evaluated including different local cementitious materials with different contents and local aggregates with different grading and densities. The proposed mixes of this study is verified by particle packing density models. These studies will lead to the selection of the final mix design. Eventually, the final cost and environmental friendliness of the final mix design are quantitatively compared with the typical commercial UHPFRC as introduced in the literature, to see how much successful this study is.

2. Experimental procedure

2.1. Material

Undensified Silica Fume (USF), Densified Silica Fume (DSF), Ground Granulated Blast Furnace Slag (GGBS), Fly Ash (FA) and Portland Cement type I (cement) were considered as the cementitious materials. A CEM I 52.5 N with a relative density of 3.14 was chosen as cement. The USF, GGBS and FA had relative densities of 2.2, 2.93 and 2.2, respectively. The hydraulic activity of supplementary cementitious materials for USF, DSF, FA and GGBS are 1.0, 1.0, 0.4 and 0.8, respectively. The hydraulic activity of supplementary cementitious materials is taken into account via the k-factor (concept according to EN 206−1 [37]). The chemical compositions of the cementitious materials are given in Table 3. Silica, dolomite and andesite sand were used with relative densities of 2.65, 2.86 and 2.96, respectively. The particle size distributions (PSD) of the materials used are given in Fig. 1. It's noteworthy that in Fig. 1, PSD curve of DSF is missing, since the utilized equipment could not capture DSF particle dispersion.

Table 3
Chemical compositions and LOI forcementitious materials.

	SiO_2	MgO	Al_2O_3	SO_3	K_2O	CaO	Fe_2O_3	TiO_2	Na_2O	LOI
Cement(%)	31.60	1.39	3.75	3.4	0.18	54.75	4.09	0.27	<0.01	1.77
USF& DSF(%)	84.00	1.08	0.75	0.09	3.34	2.22	1.96	0.03	0.17	5.56
GGBS(%)	34.87	8.03	14.38	1.96	0.72	37.05	0.89	0.72	<0.01	0.16
Fly ash(%)	55.14	0.81	32.17	0.13	0.76	4.50	3.61	1.50	<0.01	0.67

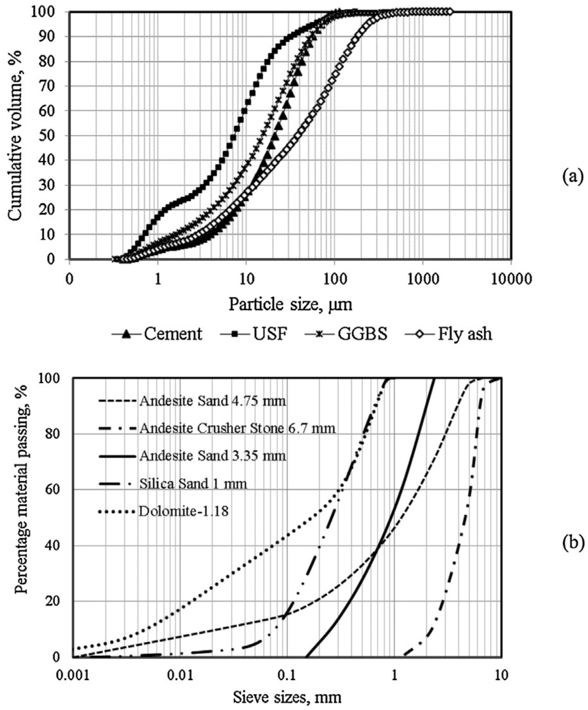

Fig. 1. Particle size distribution of, a)cement, USF, GGBS and Fly ash, b) aggregate used in this study.

Table 4
Properties of the steel fibers and admixtures.

Type of fibers	Shape	Cross section	Diameter (mm)	Length (mm)	Tensile strength (MPa)
Hook-ended	Hooked	Round	0.45	30	1000
Micro fiber	Straight	Round	0.2	13	2500
Admixture	**Physical State**	**Specific gravity**	**pH**	**Na_2O**	**CI.ion content**
Superplastecizer	Liquid	1.065	7 (±2)	1.6 %	<0.1 %
Retarder	Liquid	1.06	4 (±0.5)	<0.3 %	<Nil

The superplastisizer used is polycarboxylate-based with a relative density of 1.06 and solid content of 30 %±1%. The retarder is polymer-based unmodified phosphanates to keep the mix workable for longer. Hook-ended and straight micro steel fibers were used in the mixes. Their properties of steel fiber and admixtures are provided in Table 4.

2.2. Introduction on mix design development

To find a practical, economic and eco-friendly UHPFRC mix design with favourable mechanical properties, a step by step mix design development approach was considered in this study. This approach led to an investigation of the effects of different cementitious material types and contents (GGBS, Fly Ash and Silica Fume) and different type, size and content of aggregates (Silica sand, Dolomite and Andesite) with minimum experimental expenses within limited time span.

During step by step mix design developments, the mixtures were quantitatively tested for compressive strength with qualitative consideration of the practicality, cost-effectiveness and eco-friendliness of the mix-design (e.g. workability,

Table 5
Mix design procedure.

Material	Mix 1	Mix 2	Mix 3	Mix4	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9	Mix 10	Mix 11
Cement	900	900	875	875	875	820	830	800	665	595	545
Silica fume	300	300	290	290	175	165	250	240	200	180	180
Fly ash	300	300	145	———	———	———	———	———	———	———	100
GGBS	———	———	———	145	265	245	165	240	135	120	120
Silica sand (Max: 600 μm)	450	———	———	———	———	———	———	———	———	———	———
Dolomite sand (Max:600 μm, Min:1.18 μm)	———	450	685	750	———	———	———	———	———	———	———
Andesite sand (Max:3.35 mm, Min:0.15 mm)	———	———	———	———	790	900	915	880	———	———	———
Andesite sand (Max:4.75 mm)	———	———	———	———	———	———	———	———	1330	1035	950
Andesite stone (Max:6.7 mm)	———	———	———	———	———	———	———	———	———	445	445
Water	225	225	220	220	210	205	205	205	165	150	150
Hook-ended fiber	150	150	135	135	150	150	150	150	150	150	150
Straight fiber	———	———	40	40	150	150	———	———	———	———	———
Admixture	30	30	30	30	40	40	37	37	20	22	22
Entrapped void content (%)	9.14	9.28	3.04	2.93	0.9	0.89	1.21	1.64	2.52	0.77	1.59
RSS	187.4	293.5	228.7	232.3	198.9	129.4	141.1	163.4	61.8	28.6	62.6
Workability	Good	Good	Good	Fair	Good	Good	Good	Poor	Good	Good	Fair

utilizing less cement and fiber content, utilizing more larger aggregate and etc.); This approach led to the development of 34 mixtures for comprehensive studies of the mixes; however, for sake of brevity, only 11 mixtures with promising results are reported, as listed in Table 5 (for more information see [39,40,44]). Eventually the economic and eco-friendly impact of selected mix designs were quantitively assessed.

2.3. Mixing procedure and curing regime

The mixing procedure evolved during this comprehensive study which led to have a similar mixing procedure from Mix 5 to Mix 11. To avoid confusion, only this mixing procedure was included as follows:

Initially, all the dry materials except USF were mixed together for 1 min. Water and admixtures were added to the mix. Then, USF was added. The reason for adding it later was that this material is undensified and therefor it flies away during dry mixing. After 5 min the mix had a uniform texture, then the fibers were evenly dispersed by hand and mixed for 4 min and was ready for casting. The compaction of the cubes was done by vibrating tables for 1 min. Then, the specimens were covered with plastic sheets while they were kept in a laboratory at 24 °C and 98 % relative humidity for 24 h, followed by demoulding. Then the specimens were exposed to an associated curing regime as defined in the following.

The curing regime also evolved throughout this comprehensive study. Initially, the specimens were stored in two different curing regimes including 24 °C water (according to [38]) and 80 °C steam curing by storing the specimens in a closed bath exposing specimens to 80 °C steam until the date of testing. These regimes were applied in Mix 1–8 as listed on Table 5. In the later stage, due to economic and practical considerations (less energy consumption and ease of working with water in comparison to steam), a curing regime of water at 85 °C was also introduced and applied on Mix 9–11. Note in this paper, for sake of brevity, only the results for 11 mixtures and associated curing regimes were summarized. For more detail on curing regimes and its effects on the mechanical properties check [39,40].

2.3.1. Testing

In order to get results as soon as possible, the workability of all the mixes was compared via visual observation throughout the step by step mixture development. However, the workability of the final mix design were tested by slump test and flow table test for the mixture. These tests were conducted based on described procedure in [41,42]. In additions, for quicker result comparison, only 3-day and 7-day compressive strengths were tested on sets of three 100 mm-cubes. The cubes were tested according to the procedure prescribed in [43]. Note that further experimental investigation on mechanical properties including direct tensile strength, flexural strength, splitting tensile strength and modulus of elasticity were conducted only on the final mix design which results were reported in [44,40].

2.3.2. Particle packings of the mix designs

In this study, the modified Andreasen & Andersen model (A&A model) by Funk and Dinger [45] was utilized to evaluate and compare the particle packing of the developed mix designs.

The modified A&A model can be seen in Eq. 1:

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

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. In this study, a value of 0.23 was chosen for q [21].

The difference between the proposed mix curve and the target curve (A&A model) is calculated by utilizing an algorithm based on the Least Squares Method (LSM) as shown in **Equation 2** [46]:

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

where RSS is the sum of the squares of the residuals, P_{mix} is the proposed 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. A reduction in RSS indicates a decrease in the difference between the actual and target gradings and thus an improvement in particle packing density.

The packing densities of mixes were evaluated by measuring the densities of cast samples and comparing the actual densities with the theoretical densities based on exact mix compositions and relative densities of mix components. The difference between the measured and theoretical densities was used as an indicator of volume of the voids entrapped in the wet concrete mixture after casting and compacting.

3. Results and discussions

To have a discussion on the experimental results, initially the various proposed mixtures in this study are introduced and compared one by one against each other from compressive strength perspective with practicality viewpoints. This section is followed by Particle Packing modelling results for mixtures to check the packing density of mixtures and eventually the chosen mixtures are compared against typical commercial UHPFRC proposed in Table 1, from economic and eco-friendly perspectives

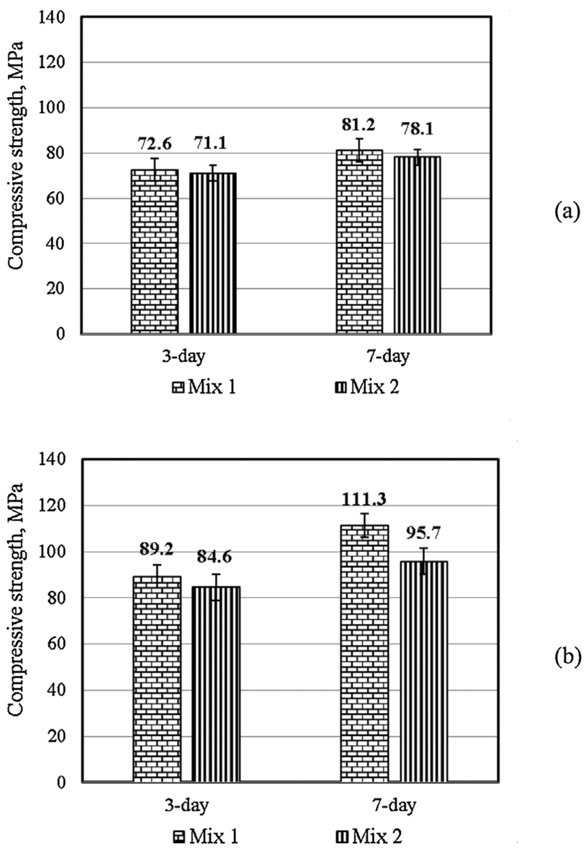

Fig. 2. Effect of silica (Mix 1) and dolomite (Mix 2) sand on compressive strength.
a) Cured in 24 °C water. (b) Cured in 80 °C steam.

3.1. Experimental results of compressive strength tests

In the first set of tests, the effect of silica sand and dolomite sand on the compressive strength was investigated. The first mix designs containing silica sand and dolomite sand are presented in Table 5, called Mix 1 and Mix 2, respectively. The water to cement ratio (by weight) was kept constant at 0.25. The retarder content was 2.5 % of the cementitious materials weight. Hook-ended steel fibers with a length of 30 mm and a diameter of 0.45 mm were used in the mixes. It is worth mentioning that in the developed mix designs, the admixture consisted of one third superplasticizer and two thirds retarder, respectively. This content ratio was determined based on the preliminary studies of trial batches which for sake of brevity was not included here (for more information see [40]).

As seen in Fig. 2, for samples kept in 24 °C water, the compressive strength of mix containing silica sand is just slightly higher than those containing dolomite sand. The compressive strength differences for samples that experienced steam curing are more pronounced. Porosities of the mixes containing silica sand and dolomite sand were found to be 9.14 % and 9.28 %, respectively. The difference between silica and dolomite sand is the density as well as the content of finer material in dolomite sand. As seen in Table 5, better packing density (lower RSS) was achieved by the mix containing silica sand. Despite the results showing that mixes containing silica sand have marginally higher compressive strength, dolomite sand was considered in further experimental work. This can be attributed to the importance of E-value as another critical early-age concrete properties for prestressed beams which has wide applications in industrial constructions. As shown in literature [47], the use of dolomite aggregate results in concrete with a higher stiffness or E-value. Therefore, the mix containing dolomite sand was chosen for further experimental work due to its impact on the practicality of the mixture.

The effect of different additional cementitious materials besides DSF on the compressive strength was established by using Fly ash (Mix 3) and GGBS (Mix 4). The ratio of either Fly ash or GGBS to cement (by weight) was kept constant at 0.17. The mix designs are shown in Table 5.

Both mixes showed similar RSS (see Table 5) indicating similar packing density. However, the results as given in Fig. 3, indicate that the concrete containing GGBS besides DSF has higher 3-day compressive strengths in comparison with concrete containing fly ash and DSF when they experience 80 °C steam, unlike when the concrete was stored in 24 °C water. Despite, no significant difference in strength found between these two mixes, GGBS is more reactive within the first days of heat

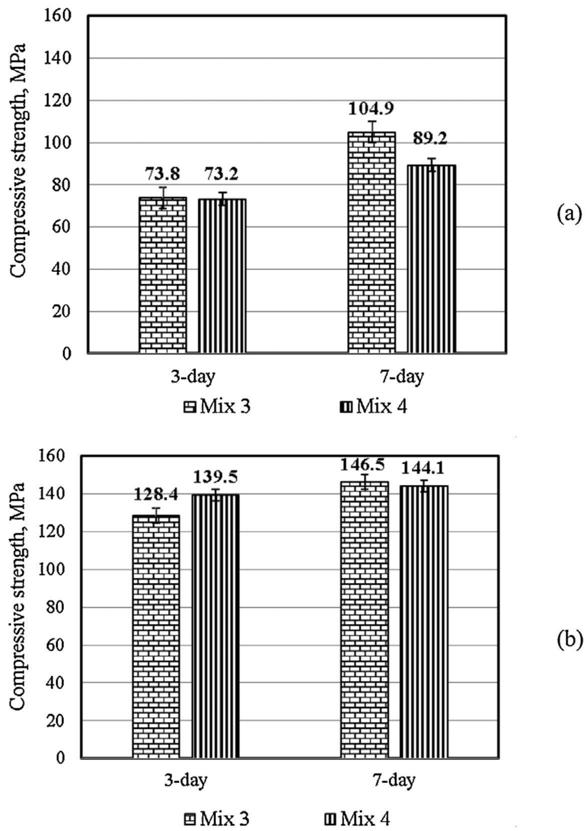

Fig. 3. Effect of Fly ash (Mix 3) and GGBS (Mix 4) as cementitious material besides DSF on the compressive strength.a) Cured in 24 °C water. (b) Cured in 80 °C steam.

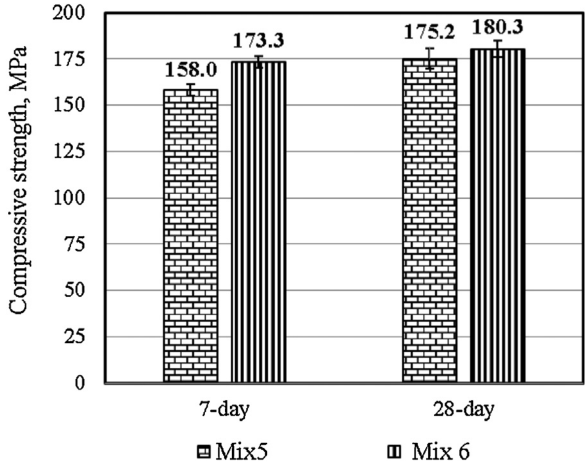

Fig. 4. Effect of aggregate content on compressive strength (cured in 80 °C steam). Mix 5 and Mix 6 containing aggregate to cement ratio of 0.9 and 1.1, respectively.

curing which is favourable for achieving high early-strength for precast products. Therefore, by taking into account this practical point, GGBS was thus chosen as a cementitious material besides DSF in the mixture.

One of the purposes of this study is making UHPFRC more economical and eco-friendly, therefore aggregate to cement ratio (by weight) was increased. The effect of aggregate content on the compressive strength was therefore established by using ratios of aggregate to cement (by weight) of 0.9 (Mix 5) and 1.1 (Mix 6). The latter ratio was taken from the studies carried out on UHPFRC [9–13,48]. After crushing the cubes for the previous mix designs, balls of silica fume was observed showing that the condensed silica fume did not disperse during the mixing procedures in the trial mix designs shown in Table 5. However, as reported in literature [49], Undensified Silica Fume (USF) is dispersed better than Densified Silica Fume (DSF), therefore, USF was used instead of DSF for further experiments. The possibility of applying coarser aggregate in the mix design was evaluated by using andesite sand with between 0.15 mm–3.35 mm size. Dolomite sand was replaced by andesite, since physical characteristics of the andesite, such as angular shape as well as rough texture provide higher mechanical interlocking between paste and aggregate leading to higher compressive strength [50,47]. The ratio of USF to cement (by weight) was taken as 0.2 based on the conducted preliminary studies for this investigation which is in good agreement with the finding of literatures [14,51]. The results for 7-day and 28-day heat cured compressive strength with different aggregate contents are presented in Fig. 4. Higher compressive strengths were achieved with higher aggregate contents. By increasing the aggregate content ratio from 0.9 to 1.1 entrapped void content reduced to 0.9 % and 0.89 % for Mix 5 and Mix 6, respectively. Note that the achieved entrapped void contents are within the suggested entrapped void content range (0.3%–5.4%) of UHPFRC as reported in literatures [51,27]. Besides, by increasing aggregate content from 0.9 to 1.1, higher packing density was achieved. Therefore, the ratio of aggregate to cement was taken as 1.1 for the next trial mix design.

The effect of higher USF content on the compressive strength was determined while the aggregate to cement ratio (by weight) was kept constant at 1.1. The weight ratio of USF to cement was increased to 0.3 (Mix 7). The mix design is shown in Table 5. In these trial mix designs, aggregates were sieved to eliminate the aggregate sizes smaller than 0.15 mm. These results were compared to those obtained for Mix 6 in which the ratio of USF to cement was 0.2. The comparison as presented in Fig. 5 shows that by increasing the ratio of USF to cement, the compressive strength increased. However, higher RSS (less fit between the two curves) was achieved, corresponding well with the higher entrapped void content which was obtained in the mix with higher USF content (Mix 7). In spite of lower packing density, higher compressive strength was achieved. This can be attributed to the fact that a higher USF content results in a higher SiO_2 (silicon dioxide) content resulting in increased pozzolanic reaction. A weight ratio of USF to cement of 0.3 was thus used for the next trial mix design. Note, due to negative impact of USF on workability, the ratio of USF to cement beyond 0.3 was not considered in this study.

In the next mix design the effect of higher GGBS content on the compressive strength was studied while the aggregate to cement ratio was kept constant at 1.1. The weight ratio of USF to cement was taken as 0.3 (Mix 8). The mix design is shown in Table 5.

From Fig. 6, it can be seen that increasing the GGBS content results in a marginal decrease in the compressive strength. Higher compressive strengths were achieved when the ratio of GGBS to cement was 0.2 and this can be attributed to the higher packing density (lower RSS). Note, due to environmental considerations (reducing cement content), the ratio of GGBS to cement below 0.2 was not considered in this study. It seems that increasing the GGBS content results in a lower packing density (higher entrapped void content) thus causing a strength reduction. For the further mix designs 0.2 was used as the ratio of GGBS to cement.

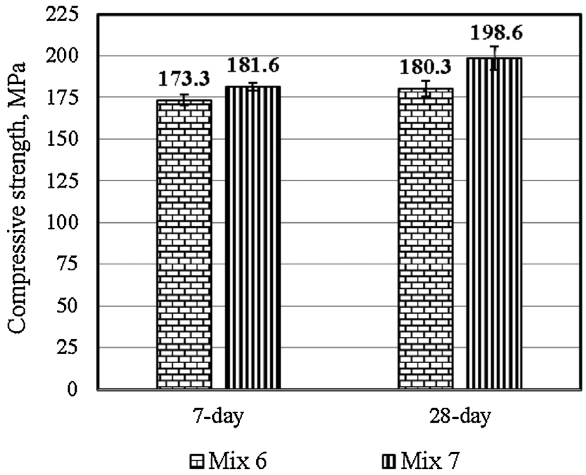

Fig. 5. Compressive strength with different USF contents (cured in 80 °C steam) Mix 6 and Mix 7 containing USF to cement ratio of 0.2 and 0.3, respectively.

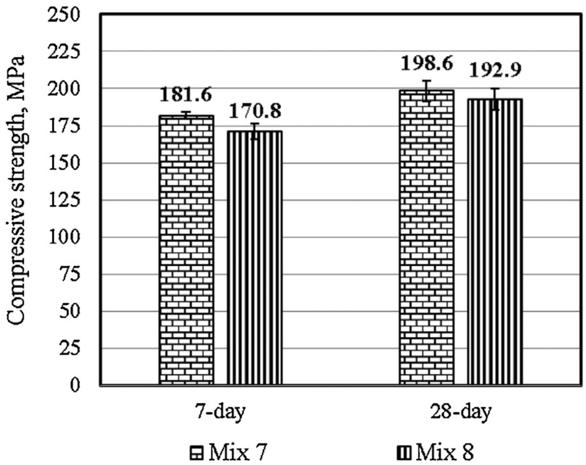

Fig. 6. Effect of GGBS content on compressive strength (cured in 80 °C steam).Mix 7 and Mix 8 containing GGBS to cement ratio of 0.2 and 0.3, respectively.

The further effect of aggregate content and size were considered next. In Mix 9, the weight ratio of aggregate to cement was 2 with the maximum aggregate size of 4.75 mm. In Mix 9, by increasing the aggregate content and size, RSS improved in comparison to Mix 8. So, increasing the aggregate content and size led to higher packed mix. This results led to further increase in aggregate size up to 6.7 mm and aggregate content (aggregate to cement ratio by weight) to 2.5 in Mix 10. It is worth mentioning that the aggregates were not sieved and were used as they were provided by the supplier. The mix designs are shown in Table 5. The ratio of sand to stone in Mix 10 was established using a dry packing density method as suggested by Mostert [52] where different sand and crusher stone combination are dropped from an elevated cone into a container. The dry packing density of the combinations is measured. The sand to crusher stone ratio which resulted in the highest dry packing density is considered to be the optimum ratio.

The effect of aggregate content and size are presented in Fig. 7. There is no significant difference between the compressive strengths obtained using aggregate to cement contents of 2 and 2.5. The main difference is the achieved densities of the mixes that was improved by increasing the aggregate content and size. As seen in Table 5, the lowest entrapped void content of 0.77 % was obtained for the mix with the higher aggregate content (Mix 10) which corresponded well with the lower RSS between the Mix 10 curve and the target curve, resulting in the denser microstructure of the concrete than the one with less aggregate content (Agg/C = 2).

For the further mix design, Agg/C = 2.5 was chosen due to the higher packing density and the lower cost.

The purpose of the next trial mix design was to increase the packing density by introducing fly ash. Fly ash was used to replace a portion of fine aggregate and cement (Mix 11). The proposed mix design is presented in Table 5.

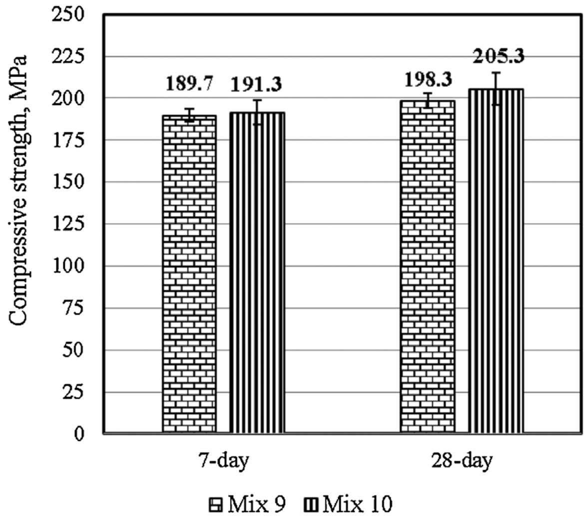

Fig. 7. Effect of aggregate content and size on compressive strength (cured in 85 °C water). Mix 9 and Mix 10 containing aggregate to cement ratio of 2.0 and 2.5, respectively.

Fig. 8 presents the comparison between the compressive strength of UHPFRC with and without fly ash as filler. The results indicate that including fly ash in the mix reduced compressive strength at 7 days and 28 days. With the addition of FA entrapped void content increased, meaning that fly ash did not work as filler.

The workability of Mix 10 was evaluated by not only using the flow table test for the mix containing no fiber and obtaining a flow of 435 mm, but also conducting slump tests with different fibers and measuring slumps between 85 mm and 120 mm [44].

Mix 10 was chosen as the final mix design due to the lowest RSS leading to the lowest entrapped void content (0.77 %) and highest compressive strength. This mix design also had the lowest cost and minimum carbon foot print (least CO_2 emission) amongst all the evaluated mix designs due to cement content and etc. which will be discussed in Section 3.3.

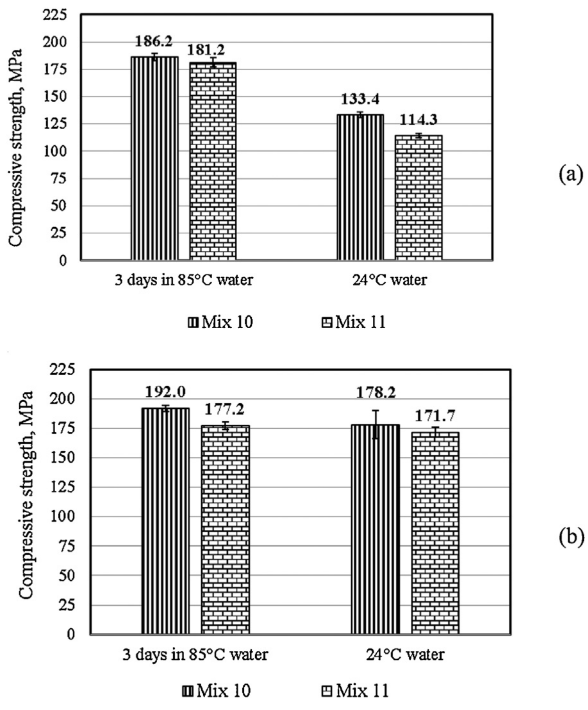

Fig. 8. Compressive strength of UHPFRC with (Mix 10)and without fly ash (Mix 11).
a) 7-day strength. b) 28-day strength.

These experimental studies show that Mix 10 has the best compressive strength in comparison with other proposed mixtures. For further investigations mixes were compared from particle packing viewpoints. In addition five mixes (Mix 2, Mix 4, Mix 6, Mix 7 and Mix 10) were chosen to be compared against the typical commercial UHPFRC reported in Table 1 from economic, eco-friendly perspectives.

3.2. Discussion on particle packings of the mix designs

After experimentally finalizing the mix design, a further complimentary studies was conducted to assess the mix designs based on the particle packing models. As known, if the particle packing of the mixes agrees well with the corresponding A&A curves (Minimum RSS), then highest compressive strengths and lower entrapped void content would be obtained.

Particle size distributions for the target and the developed mix designs curves for selected mixtures are presented in Fig. 9. In this figure, only some of the mix compositions are presented here due to trend interferences while in Fig. 10a RSS values of all the mixtures are displayed. The final mix design (Mix 10) has the best fit with a A&A model curve (Minimum RSS as shown in Fig. 10a) which corresponds well with the lowest entrapped void content (0.77 %) shown in Fig. 10b. As shown in both Figs. 9 and 10, Mix 2 has the worst fit in comparison with the other mixes (the worst RSS value), corresponding to the high entrapped void content measured for this mix.

Note that the particle packing of the final mix (Mix 10) does not perfectly fit the corresponding A&A model curve, however this mix from practicality, economic, eco-friendly viewpoints met the most favourable criteria (good workability, low cement content, larger aggregate and content and so on). In other words, from a particle packing point of view, a better highly dense mixture can be achieved to have a closer match with the A&A model. This mixture can be achieved by introducing fillers (quartz powder, Nano-silica and etc.) and fine sands in the mixtures (as suggested in [21,53,54]). However this approach has a cost penalty due to higher economic impact of those materials on the final cost of the product.

The achieved results clearly indicate that ultra-high strength can be obtained even if particles larger than 1 mm in diameter are included on condition that the packing density of the solid materials is optimized. High packed dense UHPFRC is achievable not only by using andesite, but also by using aggregates with high density that has a wider range of particle size distribution, similar to the PSD of andesite shown in Fig. 1. Particle size distribution of aggregates play a significant role in achieving highly packed UHPFRC.

3.3. Economic and Eco-Friendly discussions of mixtures

As mentioned earlier, the main concern in this study was manufacturing an economic and green UHPFRC in South Africa with practical viewpoints (no milling, no expensive curing methods, minimising sieving process, using only standard available equipment in regular concrete laboratories, using local materials, as discussed earlier). In that regard, one of the introduced factors to check both the environmental impact and strength of UHPFRC is investigating on Cement Strength Contribution Index (CSCI) which is defined by normalizing the cement contents of mixtures with their corresponding 7-day

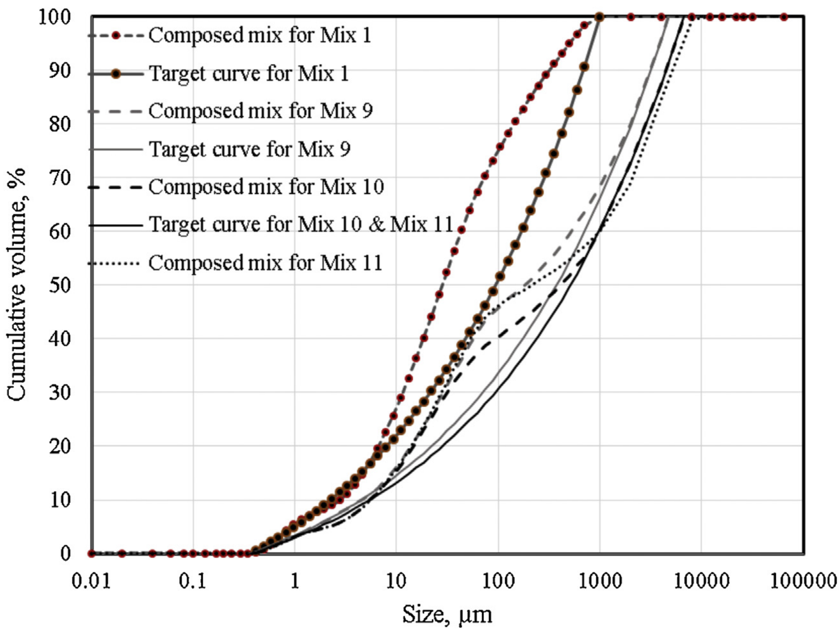

Fig. 9. Particle size distribution for the target and the developed mix designs curves for selected mixtures.

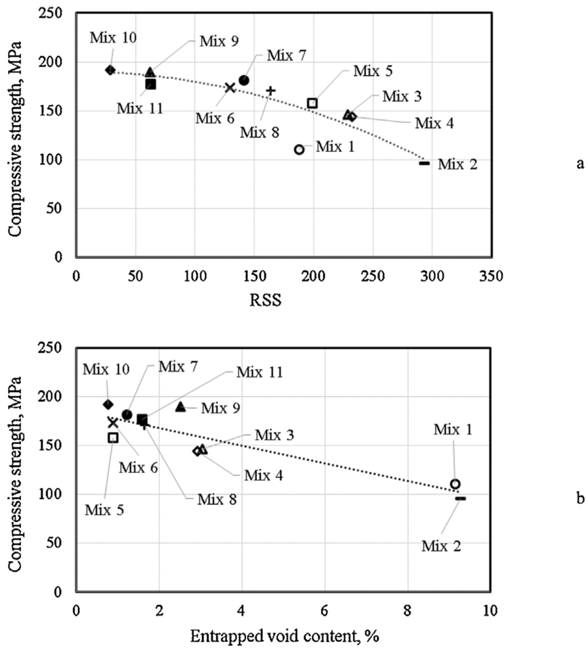

Fig. 10. Compressive strength versus a) RSS and b) Entrapped void content, of proposed mixtures.

comprehensive strength. The CSCI is an interesting factor which should be minimized from environmental perspective. This index shows the effective utilization of the cement content in a mix design. I.e. how a mix design can achieve the highest compressive strength with the minimum cement consumption. Fig. 11 compares the CSCI of various developed mixtures as well as the typical commercial mixture (listed in Table 1). As listed in Table 5, the cement consumption of proposed mixtures of this study reduced step by step from 900 kg/m^3 to 595 kg/m^3 while their associated strength increased from 95.7–191.1 MPa; therefore, the CSCI of mixtures reduced step by step and gradually from 7.8 until it reaches to 2.6 as the minimum value for Mix 10. This index in comparison with typical commercial mixture (as the reference case) has improved by about 10 %. It's noteworthy during mix developments the cement content ratios below 595 kg/m^3 was tested however, the results were not promising and excluded here for sake of brevity (for more information see [40]).

Another important environmental insight of mixtures is checking the embedded CO_2 (e−CO_2) emission of raw materials in the proposed mixtures due to the fact that the impact of transportation and production on e−CO_2 is small [55]. The e−CO_2 of each individual raw materials was calculated by multiplying the unit volume weight of the material with the corresponding e−CO_2 of the material. Therefore, the total e−CO_2 of the mixtures can be calculated by summation of e−CO_2 of mixture raw materials. The e−CO_2 of raw materials for UHPFRC mixtures are listed in Table 6. As shown in this table, based on

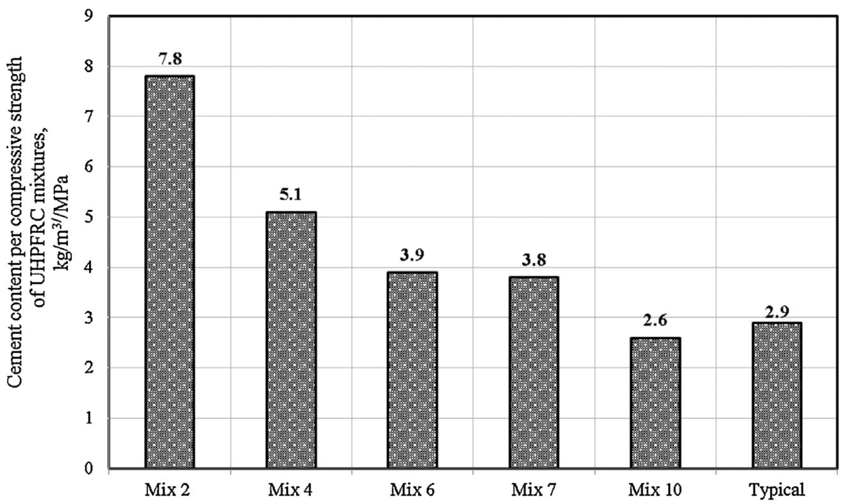

Fig. 11. Comparison of Cement Strength Contribution Index (cement content per compressive strength of UHPFRC mixtures).

Table 6
e−CO_2 of Raw materials.

Material	e-CO_2 of raw materials	References
Cement	0.83	[55,56]
Silica fume	0	[56,57]
Fly ash	0.009	[55,56]
GGBS	0.019	[55,56]
Fine aggregate	0.003002	[58]
Course aggregate	0.003998	[58]
Steel fiber	1.4965	[56,57]
Admixture	0.72	[55,56]
Quartz sand	0.01	[56,59]

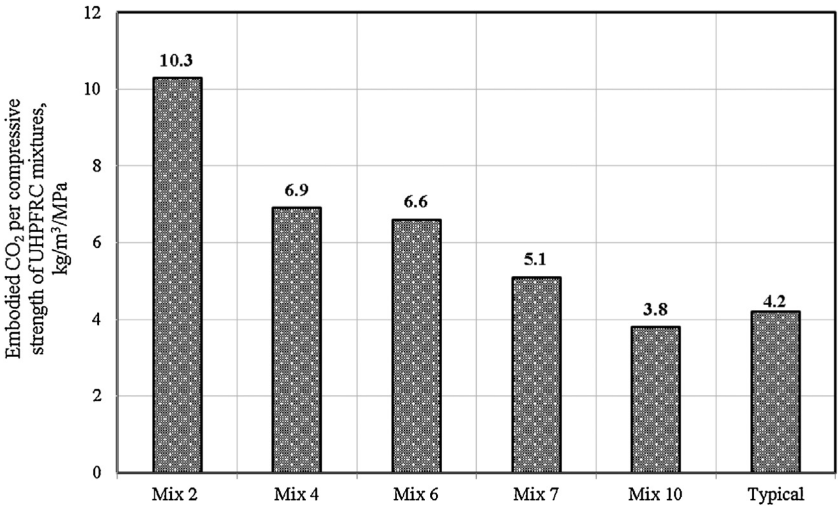

Fig. 12. Comparison of E−CO_2 Index (embedded CO_2 per 7-day compressive strength) of UHPFRC mixtures).

the typical content of cement and steel fiber in UHPFRCs, one can conclude that these two materials have the highest environmental impacts in manufacturing UHPFRCs.

To have more insightful understanding of the environmental impact and strength of UHPFRC, the Embodied CO_2 (E−CO_2) Index is defined as the embedded CO_2 of mixture normalized by its 7-day comprehensive strength. This Index shows per 1 MPa of a mixture how much CO_2 is embedded in the mixtures which should be minimized from the environmental perspective. Fig. 12 compares the E−CO_2 Index of mixtures against the typical commercial UHPFRC mixture (as the reference point) (introduced in Table 1). As shown in this figure, throughout the development of the mixtures, the E−CO_2 Index gradually decreases and eventually reached 3.8 $\frac{kg/m^3}{MPa}$ in the final mix design (Mix 10) which is about 10 % lower than the E−CO_2 Index of the reference mixture (introduced in Table 1).

Improving the economic aspect of UHPFRC is the other important aim of this work. As stated before, high manufacturing cost including material cost leads to a limited use of UHPFRC in industry. This concern was addressed in this study by increasing the aggregate content and sizes, using supplementary cementitious materials beside cement, focusing on local materials and only standard equipment of typical concrete laboratories along with eliminating some procedures e.g. milling, expensive curing methods, sieving processes as regularly introduced in commercial UHPFRC manufacturing processes. However, this paper only focuses on the material cost of UHPFRC. To have a better understanding on the impact of different manufacturing factors in large-scale UHPFRC products including material, labour costs, power consumption and etc., check Vatannia [40].

Fig. 13 compares the unit cost (USD/m^3) normalized by the 7-day compressive strength (USD/m^3/MPa) of the UHPFRC mixtures. The results are compared to the unit cost per compressive strength of the typical UHPFRC (see Table 1). The unit cost included the costs of all ingredients for producing the UHPFRC mixtures, except for transportation costs. The unit cost of cement (CEM I 52.5 N), SF, USF, GGBS, dolomite sand, andesite sand, admixtures and steel fiber are 118.5, 153.4, 173.4, 51.5, 17.0, 20.7, 147.8 and 1527.0 USD/ton, respectively. The unit costs per compressive strength for Mix 2, Mix 4, Mix 6, Mix 7 and Mix 10 are 4.2, 3.2, 3.7, 2.3 and 2.0 USD/m^3/MPa, respectively. It is noteworthy that the unit cost per compressive strength in the typical mix design was reported 7.6 USD/m^3/MPa by [60]. This significant cost reduction can be attributed to the fact that

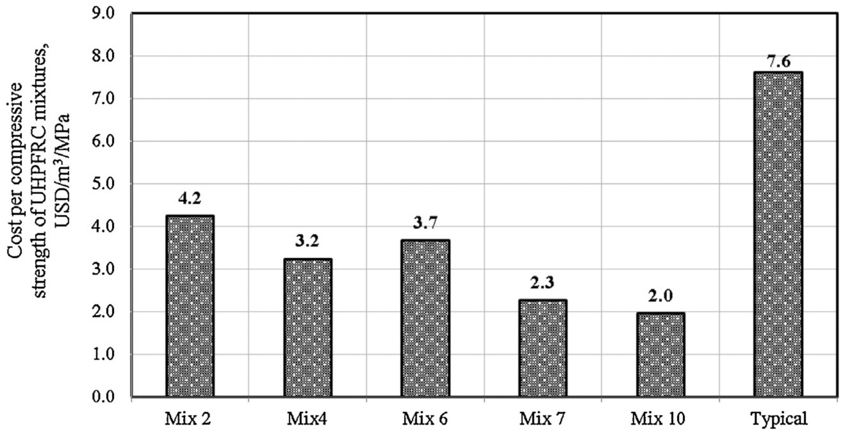

Fig. 13. Unit cost per unit compressive strength of UHPFRC mixtures.

in the proposed mix designs (Mix 10) not only supplementary cementitious materials were used, but also fine sand and quartz ground were replaced by coarser aggregate size and higher aggregate content as well as utilizing less fiber and cement content.

4. Conclusion

Economical, practical and green UHPC can be manufactured with local materials for use in large-scale applications. This accomplishment is possible as a results of high packing density approach and several modifications to the typical UHPFRC mix design. The achievements of this paper are as follow:

- UHPFRC can be achieved with large particles if the packing density of the solid materials is optimized. The highest strength is achieved when the PSD is optimized regardless of aggregate type, cement content, or composition in the optimum packing density model.
- From mechanical perspective, the optimized concrete mix compositions (Mix 10) reaches the 7-days comprehensive strength 192 MPa by steam curing which is competitive with reported typical commercial UHPFRC (180–225 MPa)
- From economic perspectives, the proposed UHPFRC is almost 75 % cheaper than the typical commercial UHPFRC.
- From environmental perspective, both the cement content and E–CO_2 Index per compressive strength of the proposed UHPFRC are 10 % less than commercial typical UHPFRC.

Declaration of Competing Interest

The authors reported no declarations of interest.

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