Chapter 8

Utilization of By-Product Materials in Ultra High-Performance Fiber Reinforced Cementitious Composites

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http://dx.doi.org/10.5772/intechopen.74376

Abstract

This chapter presents a review on the use of various industrial wastes, by-products in the development of green ultra-high performance fiber-reinforced cementitious composites (UHPFRCCs), and their effects on mechanical properties of UHPFRCC, such as metakaolin, rejected fly ash, glass powder, and palm oil fuel ash. The outcomes of this chapter would encourage the use of by-product as a supplementary cementitious material. This could be useful in protecting the environment by minimizing the volume of waste disposed on the wasteland and minimizing the emission of greenhouse gases that are released during cement production, besides contributing to cost–saving, which could somehow contribute toward the sustainability of the concrete industry.

Keywords: waste materials, green concrete, cement, concrete technology, by-product materials

1. Introduction

Ultra-high performance fiber-reinforced cementitious composites (UHPFRCCs) are defined as a concrete matrix that are characterized with a high compression strength of 150–200 MPa, a uniaxial tension strength of 7–15 MPa, and a bending strength of 25–40 MPa [1–3]. UHPFRCC is characterized with a large binder content (cement and silica fume), a large volume of steel fiber, a low water/binder ratio (W/B), and a high microsilica [4]. Accordingly, UHPFRCCs compared with normal concrete (NC) and high-performance concrete (HPC) have become popular in practical applications [5, 6]. UHPFRCCs are more efficient in producing smaller, lighter, and thinner sections due to its superior properties [5, 7].

On the other hand, an increase in the cement content implies an increase in the overall demand for cement [8, 9], which could be translated into a greater cement production, which correspondingly increases the emission of certain greenhouse gases (CO_2, etc.), in addition to increasing the concrete cost as well as the electrical energy consumption [9]. Therefore, UHPFRCC products can be considered as uneconomical construction materials and pose a threat to the environment.

Aldahdooh et al. [10] stated that there are several methods that can be employed to reduce the binder content (cement and silica fume) in UHPFRCCs. For example, (i) optimizing the mix design of concrete using mathematical or statistical methods, such as response surface methodology, and so on [11, 12], (ii) utilizing industrial solid wastes and by-products as a supplementary cementitious materials (SCMs) in producing green UHPFRCCs, such as crushed quartz (CQ) [13], fly ash (FA) [14–16], palm oil fuel ash (POFA) [10, 17], recycled glass powder (RGP) [15], activated metakaolin (AM), and ground granulated blast-furnace slag (GBFS) [15, 18, 19].

Nowadays, the utilization of solid wastes is the challenge for engineers to use friendly SCMs produced at a reasonable cost with a low environmental impact. The addition of cost-saving materials by the replacement of a considerable amount of cement reduces CO_2 emission during the manufacturer of Portland cement. Moreover, SCMs can improve the majority of fresh and hardened properties of concrete [12, 20].

Based on the above, this review focused on the second method that is particularly dependent on the utilization of wastes and by-products in developing green UHPFRCCs, including their influence on the mechanical properties of UHPFRCCs.

2. Significance of review

This review focused on the utilization of industrial wastes and by-products in UHPFRCCs. This could lead to the greater utilization of SCMs in concrete. Subsequently, it could be useful in protecting the environment by minimizing the volume of waste disposed on the wasteland and minimizing the emission of greenhouse gases. Furthermore, it contributes to cost-saving, which contributes to the sustainability of the concrete industry.

3. UHPFRCCs

UHPFRCC is an advanced reinforced cementitious material and is one of the high-strength ductile concrete (HSDC) [1, 21]. In this review, the product is generally called UHPFRCC according to [22]. In the case of mechanical performance, UHPFRCC is characterized with a super-compressive strength, tensile strength, bending tensile strength, elastic modulus, energy absorption capacity, and elastic post-cracking bending strength. In terms of durability, UHPFRCC shows an extremely dense microstructure (negligible water adsorption, water and gas permeability, and porosity) and an extremely low diffusion coefficient [1–3, 23–25].

Meanwhile, in the case of sustainability, this type of concrete still needs to be evaluated with regard to their high binder content (especially the cement content) relative to the regularly used mixtures [25].

3.1. Principles of UHPFRCC composition

The principles applied in UHPFRCC matrix development can be detailed based on previous studies:

1. Removal of coarse aggregate to enhance concrete homogeneity [3]; the recommended mean aggregate size used in producing UHPFRCCs is less than 1 mm and the aggregate-cement ratio can be up to 1.4 [21, 26].
2. Optimization of granular mixture [1, 3, 27]; ultrafine powder is added for the composition of fine-grained mixture, such as silica fume, fly ash, and so on. **Figure 1** shows the physical effect of ultrafine powder (e.g., silica fume), as
   - Filler between the cement particles,
   - Lubricant,
   - Psozzolanic materials because this substance reacts chemically with calcium hydroxide ($Ca(OH)_2$) that is also written as (CH). These substances produce compounds with cementitious properties (calcium silicate hydrates (C-S-H)/"cement gels"). This finding is reflected automatically by the decrease of porosity in the bulk and particularly in the interfacial zone. These materials improve the mechanical properties of the cement paste by reacting with CH.
3. Decreasing the W/C ratio using high-range water-reducing admixture; this maintains the small spacing of the cement grains, which decreases the space for the interfacial zone formation [1].
4. Optionally, post-setting heat treatment to enhance mechanical properties of the microstructure [1, 28].
5. Optionally, the application of pre-setting pressure for better compaction [1, 28].

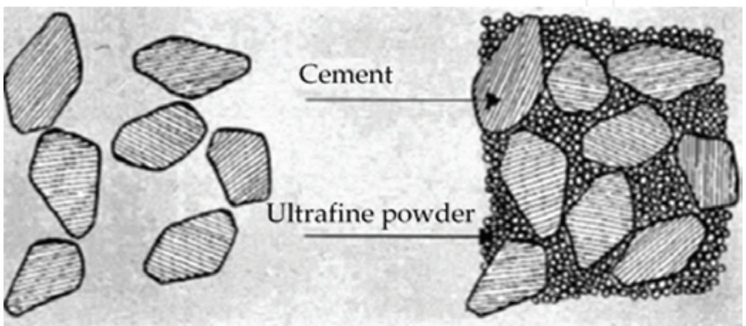

Figure 1. Ultrafine powder acting as "filler" between the cement particles [1].

3.2. Constituent materials and mix proportions of UHPFRCCs

In general, UHPFRCC is characterized as a composite that has a large content of cement and silica fume, a large volume of steel fiber, a high dosage of superplasticizer (SP), a low water/binder ratio, and the absence of coarse aggregates that are larger than 4 mm [4]. **Table 1** shows a summary of the ranges of UHPFRCC compositions and the average material properties. One example of UHPFRCCs is known under the trade name, CARDIFRC [22, 29, 30].

More details about the function of each ingredient in the UHPFRCC mix are presented in the following subsection.

3.2.1. Cement

Normally, ordinary Portland cement (OPC) can be used to produce UHPFRCCs [13, 35, 36]. UHPFRCC is characterized with a high cement content, which can be as high as 1000 kg/m^3 (**Table 1**). Vernet [37] stated that in the matrix of UHPFRCCs, not all of the cement contents become hydrated because of a low water content.

For a given W/C, the strength of concrete is largely dependent on cement content. Increasing the cement content does not improve the strength, after the required content is reached [38, 39]. A high cement content both increases air permeability and chloride penetration and may cause shrinkage-related-cracking problems [40–42], which will shorten the longevity of concrete, thus decreasing its performance (durability and strength). To prevent these problems,

		UHPFRCCs (kg/m^3)	**CARDIFRC [2, 22, 29, 30]**
Matrix composition	Portland cement	(700–1000) [1, 31]	744–855
	Coarse aggregate	(0–200) [1, 31]	0
	Fine aggregate	(1000–2000) [1, 31]	940–1173
	Silica fume	(200–300) [1, 31]	178–214
	Water	(110–200) [1, 31]	149–188
	Superplasticizer	(9–71) [32]	28–55
	Reinforcement/fibers	(>150) [1, 31]	468
	Water/cement ratio	(<0.24) [1, 31]	0.20–0.22
	Water/binder ratio	(<0.22) [1, 31]	0.16–0.18
	Superplasticizer/cement ratio	(0.018–0.051) [32]	0.033–0.074
	Silica fume/cement ratio	(>0.25) [1, 31]	0.24–0.25
Properties	Compressive strength (MPa)	(>150) [1, 31]	>185
	Tensile strength (MPa)	(>7) [33]	12–13.5
	Modulus of elasticity (GPa)	(50–70) [1, 31]	>48
	Splitting tensile strength (MPa)	(>18) [34]	24–25
	Flexural strength (MPa)	(>25) [1, 3]	>30

Table 1. The range of UHPFRCC compositions and average mechanical properties.

appropriate cement content should be used [39]. On the other hand, for a given W/C, decreasing cement content reportedly decreases permeability [38, 39, 41].

Yurdakul [39] stated that workability is a function of W/C and cement content; increasing W/C or cement content improves workability. The workability is affected by paste volume, because the paste lubricates the aggregates [39, 41]. For a given water content, decreasing the cement content increases the stiffness of concrete having poor workability [39, 43]. Although workability is increased by an increasing cement content, it causes higher internal temperatures in the concrete during the finishing and curing processes [39]. In addition, the workability increases as the cement content (paste content) increases for a given W/C ratio and aggregate content because there is more paste to lubricate the aggregates in the mixtures [38, 39].

Aldahdooh [12] stated that no special standard is published for UHPFRCC mix design. Therefore, an ideal strategy is needed for improving the mechanical properties of UHPFRCC relative to the binder contents. This finding can be realized by optimizing the mix design of concrete using mathematical or statistical methods or by utilizing SCMs.

In the case of using the mathematical or statistical methods, the mix design of UHPFRCC is still based on trial mix; therefore, no standard has been adopted yet and no rigorous mathematical approach is available. De Larrard and Sedran [44] already optimized the ultra-high performance concrete (UHPC) mix proportion using density-packing model (solid suspension model). The optimal mix was characterized with a cement content up to 1080 kg/m^3 and silica fume was up to 334 kg/m^3. Furthermore, the mix proportion of reactive powder concrete can be optimized using the group method of data handling and genetic programming [45]. They concluded that the optimum cement amount must be approximately from 1400 to 1600 kg/m^3, and the amount of silica fume might be 20 or 25% cement content. Yu, et al. [46] recently used the modified Andreasen & Andersen particle-packing model to achieve a densely compacted cementitious matrix. They concluded that by applying this modified model, producing dense UHPFRCCs using a relatively low binder content is possible as outlined in **Table 2**. They also stated that a large amount of unhydrated cement in the matrix has been observed, which can be further replaced by fillers to improve workability and cost efficiency of UHPFRCCs.

Recently, an advanced optimization method called as a response surface methodology (RSM) has been used for optimizing the binder contents by Aldahdooh et al. [11]. They concluded that although the results indicate that the prediction by RSM was satisfactory in adjusting the amount of binders in the production of UHPFRCCs materials, these values still need to be reduced further, meaning that another method could be used to reduce the cement and silica fume contents through partial replacement of cement by external ultrafine (or by-product) materials, such as crushed quartz [13], fly ash [14–16], recycled glass powder [15], and ground granulated blast-furnace slag [15, 18, 19], palm oil fuel ash [51], as outlined in **Table 2**.

3.2.2. Silica fume

Silica fume is considered as one of the main components in producing UHPFRCCs [1, 13]. Silica fume is an extremely fine non-crystalline silica produced by electric arc furnaces as a by-product of smelting process in the metallic silicon or ferrosilicon alloy production as outlined

References		Binder (kg/m^3)					W/B	St.F. (Vol. %)	Comp. 28 d (MPa)
		C	GGBS	SF	L.S.	POFA			
[47]	Without SCMs	950	0	238	0	0	0.2	2	190
[2, 22, 29, 30]		855	0	214	0	0	0.18	6	207
[2, 22, 29, 30]		744	0	178	0	0	0.16	6	185
[48]		860	0	215	0	0	0.2	2	198
[46]		875	0	44	0	0	0.19	2.5	156
[25]		1011	0	58	0	0	0.15	2	160
[49]		960	0	240	0	0	0.16	2.5	155
[50]		1050	0	275	0	0	0.14	6	160
[5]	With SCMs	657	418	119	0	0	0.15	2	150
[46]		612	0	44	263	0	0.19	2.5	142
[46]		700	0	44	175	0	0.19	2.5	149
[51, 52]		360	0	214	0	290	0.19	6	158

SCM refers to supplementary cementitious materials; C refers to cement content; GGBS refers to ground granulated blast-furnace slag; SFrefers to silica fume; L.S. refers to limestone; W/B refers to water-binder ratio; St.F. refers to steel fiber; Comp. 28 d refers to compressive strength at day 28.

Table 2. Examples on the binder content and compressive strength of optimized UHPFRCCs.

in **Table 2**. Silica fume is a highly reactive pozzolanic material. This substance has spherical-shaped particle and is characterized with an average particle size between 0.1 and 0.2 μm. Moreover, the SiO_2 content ranges from 58 to 98% [53]. Silica fume is observed to be much finer and have a higher SiO_2 content compared with the other by-products. For a given water content, addition of silica fume more than the limited value will degrade the workability of the mix, which results from the larger surface area of silica fume [54, 55].

The main functions of silica fume in UHPFRCCs are (i) acting as a filler between cement particles, (ii) for a given water-binder ratio (W/B), improving mixture lubrication caused by particle shape (sphericity), and (iii) producing hydration products by pozzolanic activity [3, 13, 35] as presented in **Figure 2**.

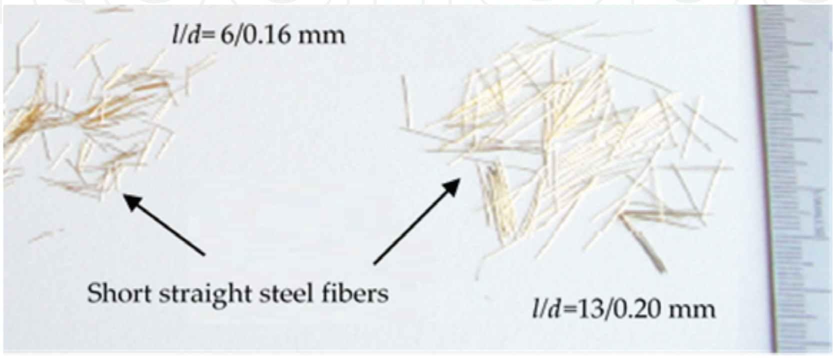

Figure 2. An example of steel fiber types used in UHPFRC [56].

The utilization of silica fume in microfiber-reinforced concrete can improve the degree of fiber dispersion, matrix interface, and interfacial zone [57], which results from the fineness of silica fume particles when compared with cement [55, 57, 58]. Furthermore, the bonding between steel fibers and matrix of steel fiber-reinforced concrete is significantly improved by utilizing silica fume. In addition, silica fume can enhance the properties of the materials used as filler [55, 58].

The theoretical amount of silica fume required for the reaction with cement product is 18% cement content [59]. The silica fume content must be practically increased from 25 to 30% cement content to obtain the densest mixture and to achieve the greatest compressive strength [1, 31, 59]. Chan and Chu [60] concluded that the highest interfacial bond strength and pullout energy between the steel fiber and concrete matrix can be obtained at a silica fume dosage of as high as 30%. The interfacial-toughening effect in the bond strength decreases when the silica fume content increases to 40%.

3.2.3. Fiber reinforcement

UHPFRCCs without reinforcement with fibers may exhibit high strength but are extremely brittle. The additional function of fibers in UHPFRCCs is enhancing ductility in tension and improving its tensile capacity [1, 13, 26].

UHPFRCC mix is generally characterized with a steel fiber content that is more than 2.5% of its volume as outlined in **Tables 1** and **2**. The dimensions range from 0.1 to 0.25 mm in diameter and from 6 to 20 mm in length with a tensile strength of more than 2000 MPa [21, 34]. For example, a large amount (up to 6% by volume) of brass-coated short straight steel fibers (6 and 13 mm) with 0.16 mm diameter has been used in CARDIFRC materials [22, 29]. The short fiber was used to enhance flexural and tensile strength, whereas the long fiber was used to increase toughness. Generally, the long steel fiber enhances the roughness of matrix by enhancing the tensile strength and strain capacity at the breakage stage at the same time, while the short steel fiber improves the tensile strength of matrix more than strain capacity at the breakage stage [22, 29].

Vande Voort et al. [13] stated that fiber size and aggregate size in any concrete mix are considered as the main factors that influence mix workability. Hence, in the absence of coarse aggregates, fiber size is considered as the primary factor influencing concrete flow (e.g., UHPFRCCs). Moreover, UHPFRCC workability tends to decrease with an increasing fiber content [13, 61].

The steel fiber-reinforced concrete with a high workability has a high probability of experiencing steel fiber segregation, which automatically reflects mechanical properties and concrete performance [62].

3.2.4. Superplasticizer

W/C ratios used in producing UHPFRCCs are generally less than 0.20, which lead to a notable reduction in the porosity of UHPFRCC matrix; this reduction in porosity increases impermeability. Thus, significant improvement on the strength and durability of UHPFRCC matrix is observed; however, special SPs should be used to have adequate flowability [63].

SPs are chemical admixtures used for reducing water demand. They are also known as high-range water reducers (HRWR) [64]. Ultra-high-range polycarboxylic ether-based (PCE-based) SPs are commonly used to have adequate concrete UHPFRCC flowability. Thus, UHPFRCC behaves similar to self-compacting concrete. Therefore, UHPFRCC can be used for casting very slender elements [34, 36, 63].

Alsadey [65] concluded that compressive strength decreases if the applied SP dosage is beyond the optimum dosage because segregation and bleeding phenomena will occur. This finding can affect concrete uniformity and cohesiveness.

3.2.5. Sand

The fine aggregate (sand) functions by confining the cement matrix to add strength [13, 66]. Yurdakul [39] and Shilstone and Shilstone [67] revealed that an insufficient amount of sand induces the segregation of mixture and increases mix flow. By contrast, increasing sand content causes stiff mixture because the sand has a high water requirement due to its high specific surface area. Moreover, workability decreased as the cement content decreased for a given W/C and aggregate content because of inadequate amount of paste that lubricates the aggregate [38, 39, 68, 69].

Quartz sand is usually used for UHPFRCC production. This sand type is not chemically active in the cement hydration reaction [13, 66]. As outlined earlier, UHPFRCC is characterized as a composite that has a large volume of steel fiber and lacks coarse aggregates that are larger than 4 mm [4].

The recommended mean aggregate size used in producing UHPFRCCs is less than 1 mm, and the aggregate-cement ratio can be up to 1.4 [21].

3.2.6. Water

Generally, decreasing the W/C will decrease the permeability, the porosity of the paste decreases and concrete becomes less permeable thus reducing the passage of water and aggressive compounds such as chlorides and sulfates, thus the durability and strength increased [39, 41, 70]. Increasing W/C will increase workability [70]. Strength is considered to be a function of W/C [38, 39, 41]. To increase strength, thus, the W/C should be reduced; it is more efficient to reduce the water content than to use more cement [39].

Improving the relative density of concrete is the main goal in producing UHPFRCCs and not water content reduction. Several researchers optimized the water-binder ratio (W/B) for UHPFRCCs. Wen-yu et al. [71] reported an optimum W/B ration of 0.16 based from their experimental work. **Table 3** summarizes the mean and range for the W/C ratios and W/B ratios used in UHPFRCCs. The used W/B ration in producing UHPFRCC was in the range of 0.10–0.25, while for W/C it was found to be in the range of 0.13–0.37.

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Properties	Low	Mean	High
W/B	0.10	0.17	0.25
W/C	0.13	0.22	0.37

Table 3. Classification of W/B and W/C ratios for UHPFRCCs summarized by Vande Voort et al. [13].

4. Utilization of by-products in UHPFRCC

Based on the earlier sections, there are several types of by-products or industrial wastes other than SF that can be used as an SCM or as an additive material in UHPFRCC products. Some of these wastes are metakaolin (MK), rejected fly ash, ground-granulated blast furnace slag, rice husk ash, recycled glass powder, palm oil fuel ash, and so on. The general chemical and physical properties of some of these SCMs and ordinary Portland cement (OPC) are summarized in **Table 4**. The influence of some of these SCMs on mechanical properties of UHPFRCC is described in the following subsections.

4.1. Metakaolin

Metakaolin (MK) is considered as a by-product material that is manufactured from kaolin clay. MK is a very fine-white clay mineral that has been traditionally used in porcelain production.

	OPC	FA	r-FA	GGBS	SF	MK	GP	RHA	UPOFA
SiO_2	20.44	35–60	47.23	34.4	91.4	53.87	71.4	88.32	65.01
Al_2O_3	2.84	10–30	24.54	9.0	0.09	38.57	1.4	0.46	5.72
Fe_2O_3	4.64	4–20	8.42	2.58	0.04	1.4	0.2	0.67	4.41
CaO	67.73	1–35	8.28	44.8	0.93	0.04	10.6	0.67	8.19
MgO	1.43	1.98	1.62	4.43	0.78	0.96	2.5	0.44	4.58
SO_3	2.20	0.35	0. 39	2.26	0.01	—	0.1	—	0.33
Na_2O	0.02	0.48	—	0.62	0.39	0.04	12.7	0.12	0.07
K_2O	0.26	0.4	—	0.5	2.41	2.68	0.5	2.91	6.48
MnO	0.16	—	—	—	0.05	0.01	—	—	0.11
TiO_2	0.17	—	0.99	—	0.0	0.95	—	—	0.25
Specific gravity	3.05	2.2–2.8	2.19	2.79	2.6–3.8	2.5	2.48	2.11	2.55
Particle size (μm)	10–40	≤45	>45	—	0.1	0.5–20	<45	11.5–31.3	2.06
Specific surface (m^2/g)	1.75	5–9	0.119	0.4–0.599	16.455	12.174	0.756	30.4–27.4	1.77

OPC, refers to ordinary Portland cement; GGBS, refers to ground-granulated blast-furnace slag; SF, refers to silica fume; FA, refers to fly ash; r-FA, refers to rejected fly ash; GP, refers to glass powder; RHA, refers to rice husk ash; MK, refers to metakaolin; POFA, refers to palm oil fuel ash.

Table 4. Chemical and physical properties of OPC and mineral admixtures (%) [12, 72–74].

MK is considered as highly pozzolanic materials, where major constituents of MK are SiO_2 and Al_2O_3, as tabulated in **Table 4** [75].

Table 4 shows that MK is characterized with the highest alumina content compared with other mineral admixtures and OPC, showing the capability to produce strengthening gel, that is, calcium aluminates hydrate (CAH) by reacting with the primary hydrate of cement. Moreover, MK has a considerable silica content which produce calcium silicate hydrate (CSH), by reacting with calcium hydroxide [72].

Nuruddin et al. [72] studied the effect of MK and the aspect ratio (*l*/*d*) of fibers on the mechanical properties of high-strength ductile concrete (HSDC) with constant slump (50 ± 10) as shown in **Figure 3**.

Nuruddin et al. [72] concluded that as the MK content increases the mechanical properties improved as shown in **Figure 3**. Among all the mix, the highest strengths have been observed with 10% MK and 2% volume fraction.

MK develops a high pozzolanic activity, however, degrading workability. Moreover, MK is its high embodied CO_2 generated for the production of one ton of MK, which is about 330 kg/ton compared with silica fume and fly ash 14 and 4 kg/ton, respectively. On the other hand, MK is characterized with a faster strength development along with a lower drying shrinkage compared with plain cement and silica fume [76].

4.2. Rejected fly ash

Kou and Xing [15] stated that more than 1 million tons of fly ash is produced annually in Hong Kong, as a by-product of electricity generation, where the finer fraction (f-FA) produced by passing the raw materials of ash via a classifying process is routinely used in the production of blended cements for construction. f-FA has a fineness requirement of not more than 12% by mass retained on the 45-μm test sieve. However, the remaining proportion is rejected due to its large particle size. In Hong Kong, this rejected fly ash (r-FA) has to be disposed of in large lagoons, creating an ever-increasing environmental hazard. Effect of r-FA and steam curing on mechanical properties of UHPFRC is shown in **Figure 4**. The chemical and physical properties of r-FA are tabulated in **Table 4**.

Kou and Xing [15] concluded that as the r-FA replacement level with silica sand increases, the mechanical strengths of UHPRCC tend to increase compared with the control mix. This increase in strength due to the replacement of fine aggregate with r-FA is attributed to (1) the improvement of packing density with r-FA and (2) the pozzolanic action of r-FA. However, the rate strength development decreases with the increase in r-FA content. This is due to the fact that r-FA reacts very slowly with calcium hydroxide liberated during the hydration of cement and does not contribute significantly to the densification of the concrete matrix at early ages. The highest replacement level is reached up to 50%.

4.3. Glass powder

Jin et al. [77] stated that the recycling process of glass is considered as a major problem in urban areas of developed countries.

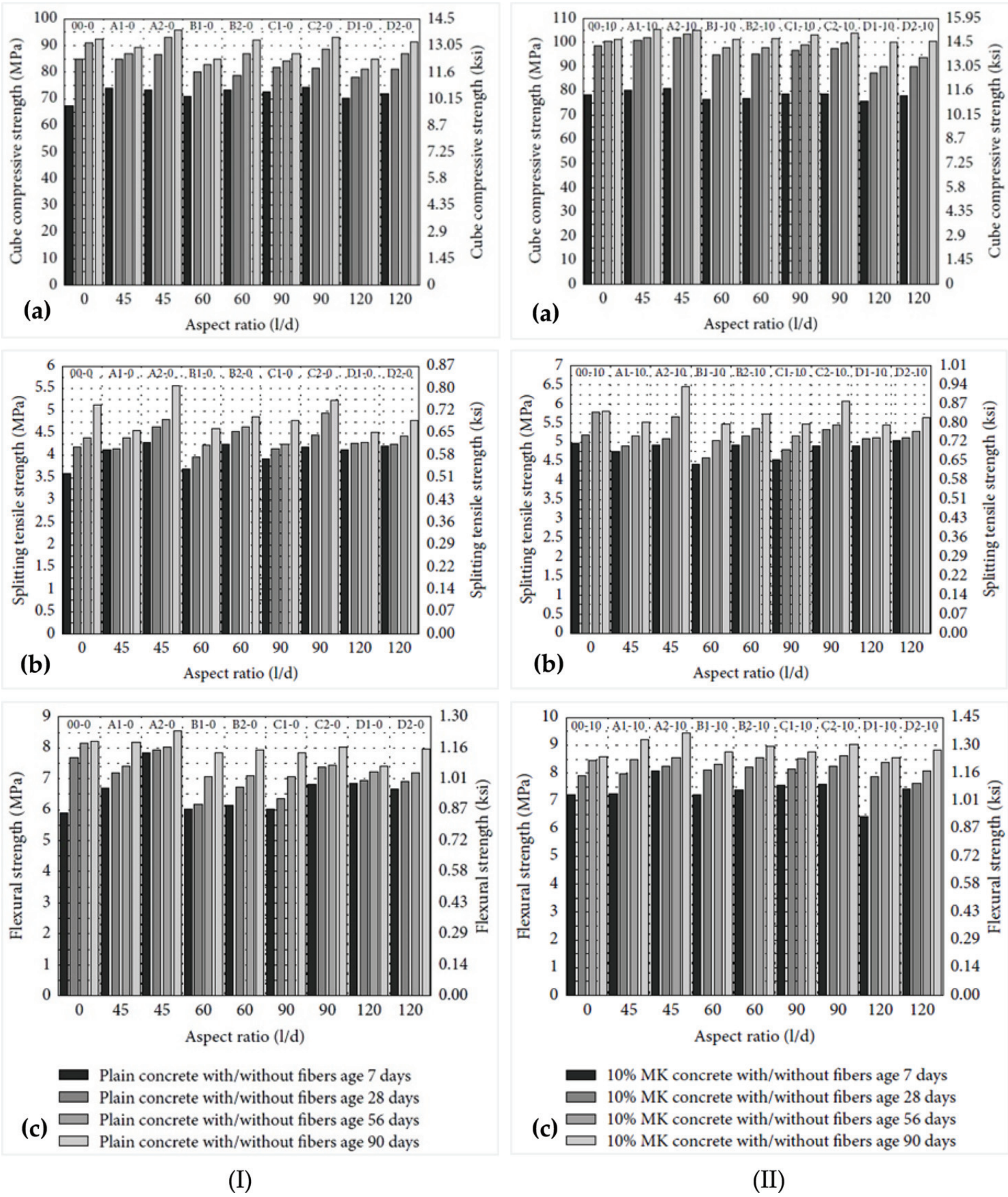

Figure 3. Influence of MK and fibers on mechanical properties of HSDC: (I) Plain concrete and (II) MK concrete: (a) Compressive Strength, (b) Splitting Strength, and (c) Flexural Strength [72].

Glass has been used in the concrete production as a crushed glass, as a raw siliceous material in the production of Portland cement [78], and as a hydration-enhancing filler [78].

Jin et al. [77] stated that glass powder (GP) is considered as amorphous and characterized with a high silica content. A particle size of 45 μm or less is reported to be favorable for pozzolanic reaction [15, 79].

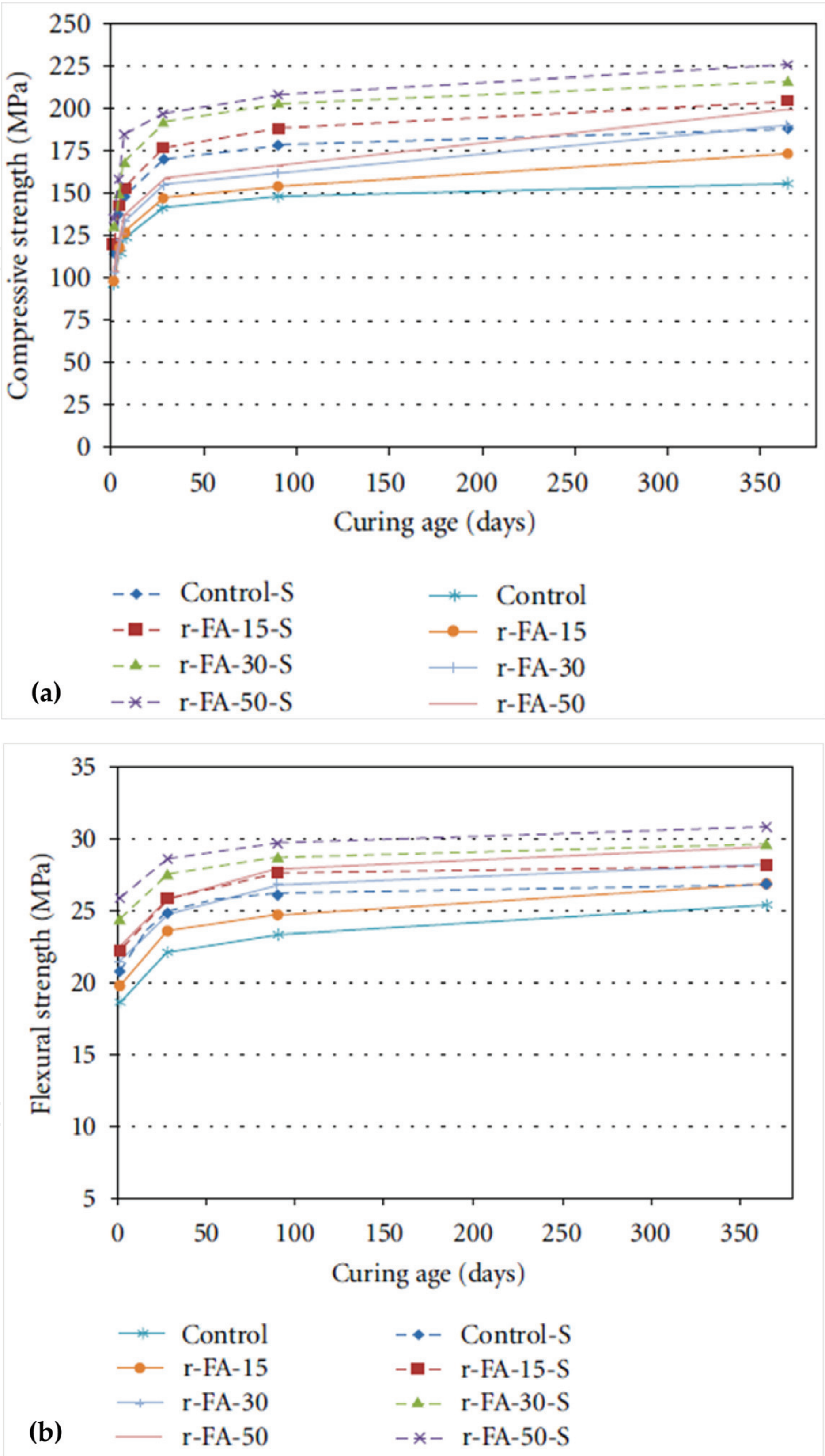

Figure 4. Influence of r-FA and steam curing (S) on mechanical properties of UHPFRC: (a) Compressive strength and (II) Flexural strength [15].

Several studies [80, 81] have showed that a cement replacement between 10 and 20% yields the highest strength, while fine aggregate replacement of up to 40% has little effect on compressive strength.

Kou and Xing [15] utilized the GP as supplementary cementitious materials in UHPFRC. The effect of GP and steam curing on mechanical properties of UHPFRC is shown in **Figure 5**. The results showed that the replacement of cement by glass powder decreased the early (before 7 days), but increased the later (after 28 days) strengths of UHPFRC, at all ages. The highest replacement level reached up to 30%.

4.4. Palm oil fuel ash

Palm oil fuel ash (POFA) is a by-product of burning: empty fruit bunches, kernel shells, and fibers, which are used in generating electricity for the boiler of palm oil mills [82, 83].

Palm oil industry is one of the major agro-industries in countries, such as Malaysia, Indonesia, and Thailand [84]. Most of the POFAs are disposed as waste in landfills, which may contribute to environmental problems in the future [85]. Therefore, a lot of research works have been conducted to find a suitable solution for proper POFA disposal.

Many researchers have found that POFA has pozzolanic qualities and properties in concrete. In fact, POFA can be considered as a pozzolanic material [86–88].

Awal and Hussin [84] showed that POFA can be utilized as supplementary cementitious materials, and POFA has a high potential in suppressing expansion associated with alkali-silica reaction in concrete.

POFA has been utilized in high-performance concrete (HPC) production, the highest compressive strength was found in the range of 60–86 MPa, which was obtained at POFA (with a median particle size of approximately 10 μm) replacement level of 20% at day 28 with 550–560 kg/m^3 total binder [87, 89, 90].

Megat Johari et al. [88] modified the treatment and grinding process of POFA by heat treatment to remove the excess carbon content and to decrease the POFA median particle size to approximately 2.06 μm as tabulated in **Table 4**. A highly efficient pozzolan was obtained through their treatment processes. The modified ultrafine POFA (UPOFA) was utilized for improving the properties of high-strength green concrete (HSGC). They concluded that the compressive strength could exceed 95 MPa with a replacement level of up to 60% OPC with UPOFA.

Recently, Aldahdooh et al. [10] reduced the binder content by replacing greater portions of the cement and silica fume in UHPFRCCs with UPOFA as supplementary cementitious materials while generally maintaining its mechanical properties as shown in **Figure 6**. The results showed that the ultimate flexural and uniaxial tensile strengths increased when the replacement levels of OPC by UPOFA increased and decreased when the replacement levels of densified silica fume (DSF) by UPOFA increased. Moreover, the optimal result was the production of a green UHPFRCCs (GUSMRC) with a low cement content of 360.25 kg/m^3 and

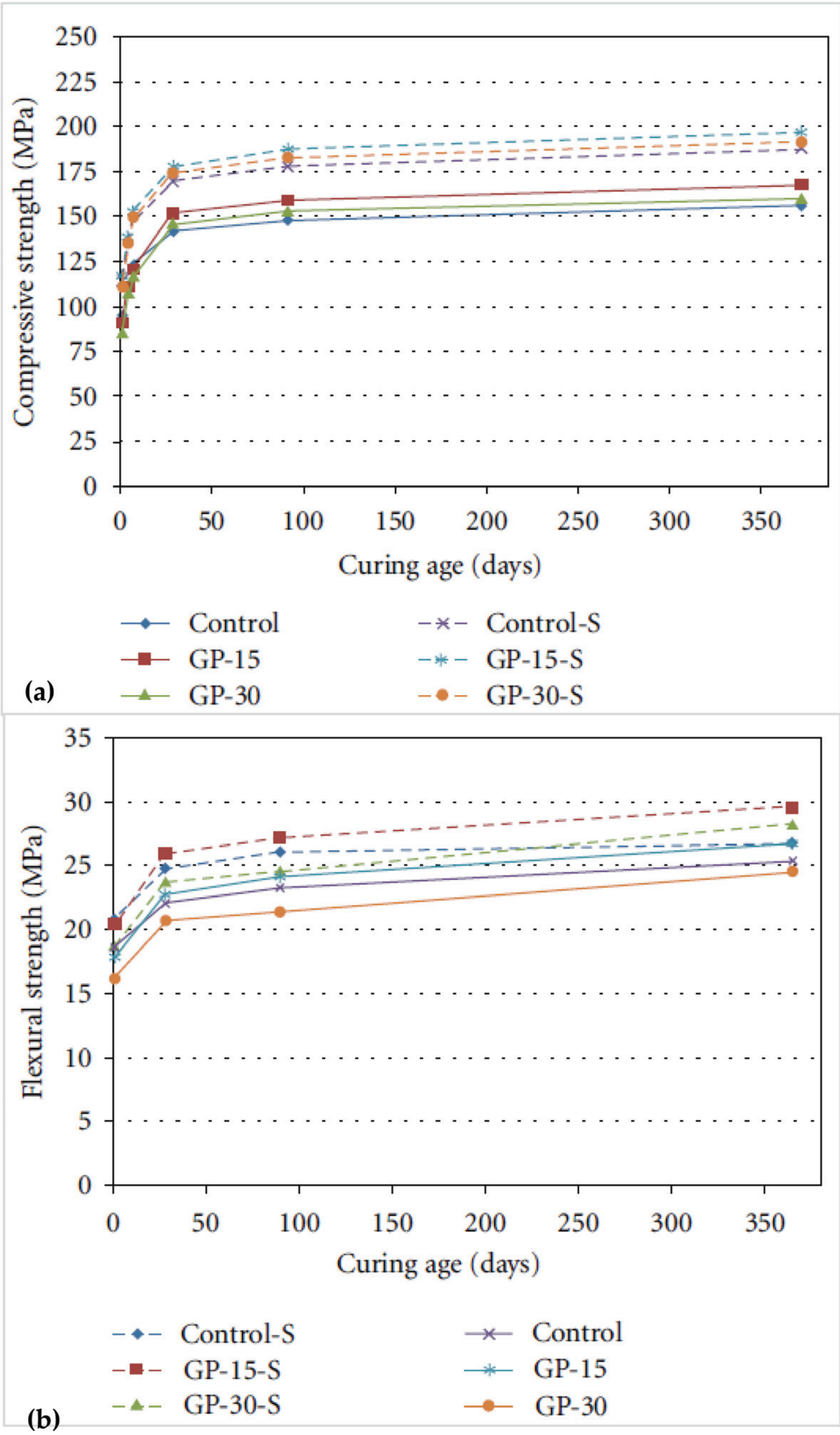

Figure 5. Influence of GP and steam curing (S) on mechanical properties of UHPFRC: (a) compressive strength and (II) flexural strength [15].

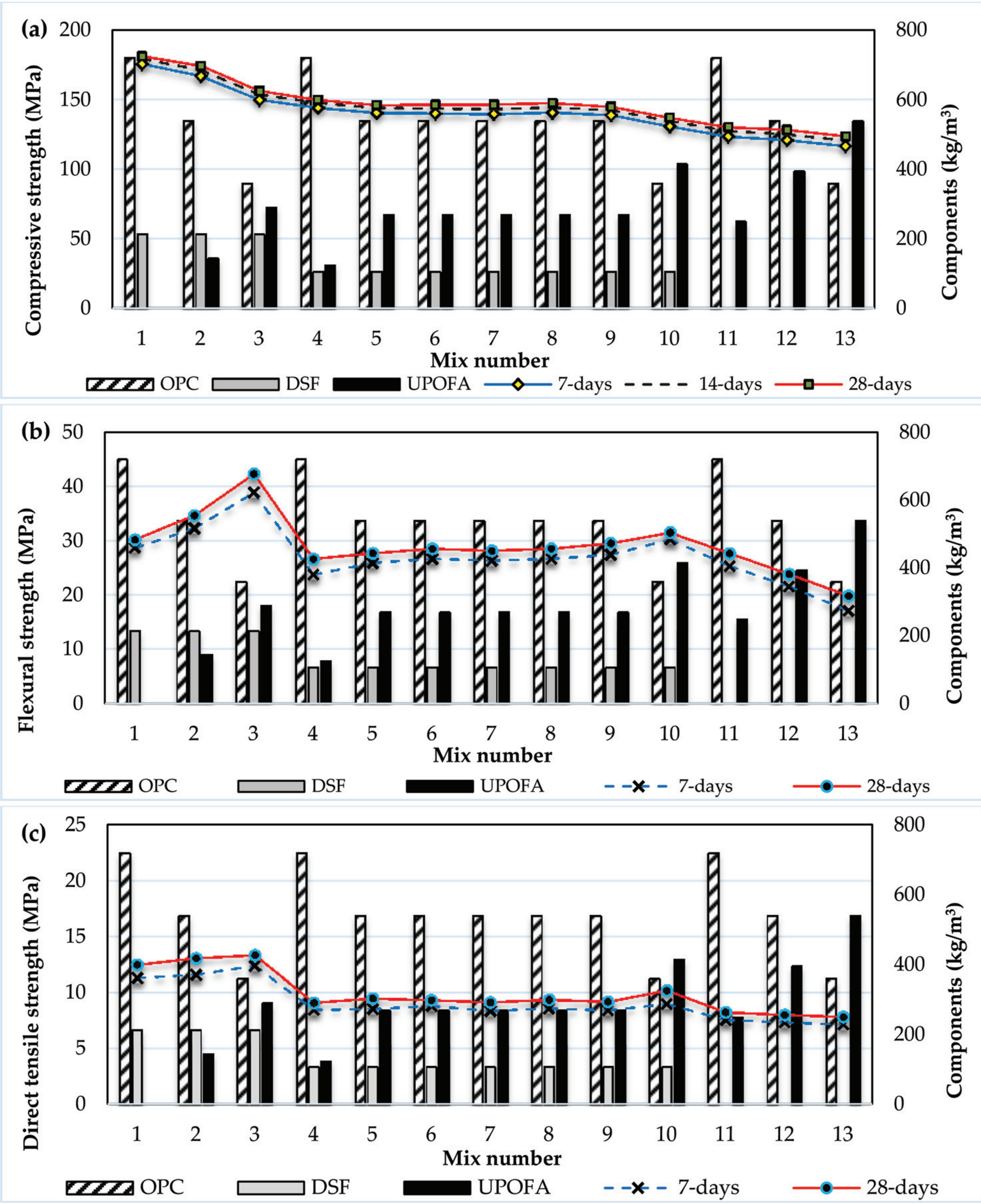

Figure 6. Effect of UPOFA on the mechanical strength of UHPFRCCs at 7 and 28 days: (a) compressive strength, (b) flexural strength, and (c) tensile strength [10, 17].

with a ultra-high compressive strength of 158.28 MPa as given in **Table 5**. Furthermore, the use of UPOFA (particularly in high volume) can contribute to a healthier and more sustainable environment, which increases green concrete products and may reduce concrete cost.

Components		(kg/m^3)
Cement		360.25
Microsilica		214.25
UPOFA		290.52
Mining sand		1057.3
Water		168.30
Superplasticizer		50.43
Steel fibers	$l_1 = 6$ mm	390
	$l_2 = 13$ mm	78
Water/binder		0.195
Microsilica/binder		0.247
Mechanical properties (28 days)	Compressive strength (MPa)	156.72
	Direct tensile strength (MPa)	13.35
	Flexural strength (MPa)	42.38
	Splitting tensile strength (MPa)	20.46
	Modulus of elasticity (GPa)	46.72

Table 5. Optimum GUSMRC mix constituents and properties [10, 17, 51].

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