Article

Use of waste from granite gang saws to manufacture ultra-high performance concrete reinforced with steel fibres

Fernando López Gayarre [1]*, Jesús Suárez González [1], Iñigo Lopez Boadella [1] Carlos López-Colina Pérez [1], Miguel Serrano López[1].

* **Corresponding author: gayarre@uniovi.es**

[1] Polytechnic School of Engineering – University of Oviedo, Campus de Viesques, 33203 Gijón, Spain; gayarre@uniovi.es (F.L.G.); suarezg@uniovi.es (J.S.G); inigo2208@hotmail.com (I.L.B.); lopezpcarlos@uniovi.es (C.L.-C.P.); serrano@uniovi.es (M.S.L.)

* Correspondence: gayarre@uniovi.es; Tel.: +34 985182278

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Abstract: The purpose of this study is to analyse the feasibility of using waste from granite gang saws (GCW-GS) to manufacture ultra-high performance, steel-fibre reinforced concrete (UHPFRC). These machines cut granite blocks by abrasion using a steel blade and slurry containing fine steel grit. The waste generated by gang saws (GCW-GS) contains up to 15% Fe2O3 and up to 5% CaO. This is the main difference from the waste produced by diamond saws (GCW-D). Consequently, the second objective of this study is to compare the results of the waste obtained with gang saws with that from diamond saws, in order to determine the influence of iron and calcium oxides. The waste from cutting granite with gang saws was used in different percentages to replace micronized quartz powder of natural origin in the manufacture of UHPRFC.

All the test specimens were analysed to determine their compressive strength, elasticity modulus, flexural strength and indirect tensile strength. The final conclusion is that wastes from both gang saws and diamond saws can be used to manufacture UHPFRC with an improvement in the mechanical properties up to a 35% replacement. The results for GCW-GS are better, mainly due to the pozzolanic effect of the iron dioxide. For higher percentage replacements the mechanical properties are close to the control concrete with small decreases.

Keywords: ultra-high performance concrete; waste; granite gang saws; steel fibres, compressive strength, flexural strength, elasticity modulus.

1. Introduction

The construction sector is one of the industrial activities that consumes the most natural resources and generates the most waste in the European Union. Most of the waste generated is mineral waste, 2/3 of the total according to "Waste statistics" [1] of the 2018 Eurostat. For this reason, many studies are being carried out into the manufacture of concrete using recycled materials or by-products from the construction sector as partial or total replacement of natural aggregates.

Among the activities that consume the most natural resources and generate the greatest amount of waste, are the extractive industry. These wastes can be extremely difficult and expensive to recycle. According to the 2018 Eurostat about waste in the European Union, the mining and quarrying sector generates 26% of the total waste, and was the second highest generator of waste in the EU in 2018 [1]. In recent years, various studies have analyzed the use of mining waste in the manufacture of concrete [2–7].

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Several of these works are aimed at replacing some of the components of ultra-high performance fibre reinforced concrete (UHPFRC), with different types of waste. N. A. Soliman and A. Tagnit-Hamou demonstrated in several studies [8–10] that glass waste could be included in ultra-high performance concrete (UHPC). They found that it was possible to replace 50% of the quartz sand with glass waste, with an average particle size of 275 μm, without affecting the compressive strength of UHPC [8]. They also showed that 20% of the cement and up to 100% of the micronized quartz could be replaced, obtaining concrete with a compressive strength of 220 MPa, a flexural strength of 29 MPa and a modulus of elasticity of 55 GPa [10]. These good results can be attributed to the pozzolanicity of powder glass, its high strength and its elastic modulus. They also observed that using powder glass as an alternative to silica fume improves the compressive strength of UHPC [9]. For a substitution of 30%, they obtained an average value of compressive strength of 235 MPa, compared to 204 MPa for the control UHPC. Their results prove the viability of an economical UHPC with good mechanical properties and a reduced carbon footprint.

Zhigang Zhu et al. [11] investigated the influence of iron ore tailings (IOT) as an alternative to fine aggregate on the properties of UHPC. The results showed a higher compressive strength of UHPC when using IOT with a maximum size of 1.18 mm as a replacement for quartz sand. The best performance was achieved for a replacement of 60%. Sujing Zhao et al. also analyzed the influence of this waste as an alternative to natural aggregate [12]. Their results show a loss of strength in the UHPC when incorporating the IOT. However, the addition of 2% steel fibres to UHPC with 20-40% IOT improves the mechanical properties, making them comparable to those of the reference concrete. Zhao attributes this improvement to a better dispersion of the fibres caused by the IOT, making a more homogeneous matrix.

Other researchers have studied the possibility of incorporating other wastes, such as copper slag. The results obtained by S. Al-Jabri et al. [13] show an increase in the compressive, flexural and tensile strength of HPC when using copper slag as an alternative to fine aggregate, always maintaining the same workability of the mixture. For a 100% replacement there are increases in compressive strength above 19%. Similarly, the results obtained by PS Ambily et al. [14] demonstrate the viability of manufacturing UHPC with a compressive strength greater than 150 MPa when incorporating copper slag.

O. Mashaly et al. [2] studied the feasibility of incorporating granite sludge as an alternative to cement in the manufacture of concrete and mortar. The results showed that for a 20% substitution, the variations in the mechanical properties are not relevant, observing an increase in resistance to abrasion and freeze-thaw cycles. For their part, S. Singh et al. [3,4] analysed incorporating granite cutting waste as an alternative to fine aggregate in order to obtain more sustainable concretes. The results show that using 25-40% cutting waste granite has a positive effect on the strength and durability of concrete. F.Kala [5] obtained similar results when incorporating granite powder as an alternative to fine aggregate in the manufacture of high-performance concretes.

Most of the studies carried out focus on the use of waste from the extractive industry to make conventional concrete or HPC, few of them focus on the use of this waste for the manufacture of UHPC or UHPFRC. J. Suárez et al. [15] analysed the influence of incorporating waste from fluorite mines as an alternative to fine aggregate in the manufacture of UHPFRC. The results show that a 70% substitution provides acceptable values of compressive strength, flexural strength, and tensile strength. In this line are the results obtained by I. López et al. [16], who substituted micronized quartz for granite cutting waste in UHPC. The properties obtained for substitutions of 70% are comparable to those of the control concrete, while, for a ratio of 35%, an increase in compression, flexural, and tensile strength of the concrete was observed.

In a previous work carried out by I. López et al. [16] the substitution of micronized quartz by fine granite waste from diamond saws cutting machines (GCW-D) (Figure 1b) was analyzed with favourable results. The results show an improvement in workability and compressive strength for a total replacement of micronized quartz. Flexural strength and tensile strength are increased for a 35% substitution, while for a replacement of 70% the values obtained show little variation with respect to the control concrete.

In the present study, as an alternative to micronized quartz, granite cutting waste from granite cutting machines called gang saws (GCW-GS) was used. This is a very economical system used as an alternative to diamond saws. With this type of machine, the granite block is cut by the abrasive effect of the forward and backward movement of steel plates watered by an aqueous mixture containing steel particles kept in suspension by the densification of the mixture with calcium oxide (CaO) (Figure 1a). These wastes are different from those used in [16] as the waste is mixed with up to 15% Fe2O3 and up to 5% CaO from the aqueous grout used in the cutting process of gang saws.

The main objective of this work is to evaluate the behaviour of UHPFRC when this waste is used. In addition, this work contrasts these results with those obtained in the previous study in which wastes free of Fe2O3 and CaO were used, in order to analyse the influence of these two substances on the mechanical properties of UHPFRC.

2. Experimental study

2.1. Materials

The cement used was CEM I 42.5 R / SR, supplied by Lafarge-Holcim S.A. (Madrid, Spain). The properties of the cement meet the requirements of the UNE-EN 197-1 standard [17], and comply with the recommendations of the EHE-08 [18]. As natural aggregates, two fractions of silica sand were used. The sands, with two granulometric fractions 0/0.5 mm and 0.5/1.6 mm, were supplied by Sílices La Cuesta (Asturias, Spain). As additions, densified silica fume (Elkem Microsilica® 940), with a mean particle size of 0.15 µm, and micronized quartz, with a maximum particle size of 40 µm,supplied by Silicas Gilarranz S.A (Segovia, Spain), were used. The short steel fibres, with a diameter of 0.2 mm and a length of 13 mm, were supplied by Arcelor Mittal (Asturias, Spain). To achieve a workable UHPFRC, a polycarboxylate superplasticizer, provided by ViscoCrete-225 Powder, (Madrid, Spain) was used. As an alternative to micronized quartz, granite cutting waste from gang saw cutting machines (GCW-GS) was used, (Figure 1a).

a) Granite gang saw cutting machine b) Granite cutting diamond saw

Figure 1. Obtaining residual granite

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Table 1 shows the values of particle density, water absorption and humidity of the materials used in this study. The particle density was determined by means of a helium pycnometer, while the specifications of the UNE-EN 1097-6 standard were followed to evaluate the water absorption of silica sands [19]. The higher density of GCW-GS, in relation to the additives used in the control concrete and GCW-D, is due to the presence of iron oxide particles.

Table 1. Density, water absorption and humidity of materials.

Property	Sand 0.5/1.6 mm	Sand 0/0.5 mm	Silica Fume	Micronized Quartz	GCW-GS	GCW-D
Bulk density (kg/m3)	2616	2616	2300	2609	2856	2633
Absorption at 24 h	0,53%	0,28%	-	-	-	-
Humidity (%)	0%	0%	< 3,00%	< 0,2%	0%	0%

Table 2 shows the chemical composition of the waste (GCW-GS), determined by X-ray fluorescence. The differences between this GCW-GS waste and the GCW-D, used in the previous article [16], are the higher content of Fe_2O_3 (14.59%), due to the presence of steel particles, and the 4.53% CaO . The higher percentage of SiO_2 is attributable to the difference in the type of granite that was cut to generate the two wastes.

Table 2. Chemical analysis (%) of the granites powder and micronized quartz.

Specimen	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	L.O.I
Micronized quartz	>99,3	0.26	0,05	-	-	0,02	-	0,04	0,05	-	-
GCW-GS	60,51	11,50	14,59	0,13	0,41	4,53	2,68	4,08	0,24	0,15	0,73

Figure 2 shows the granulometric distribution of the different materials used in this study. It can be seen that granite waste have a particle size close to micronized quartz, so that it is proposed as an alternative to replace it. Although silica fume has a maximum particle size of 0.15 µm, the particle size distribution observed in Figure 2 is due to the fact that it is densified.

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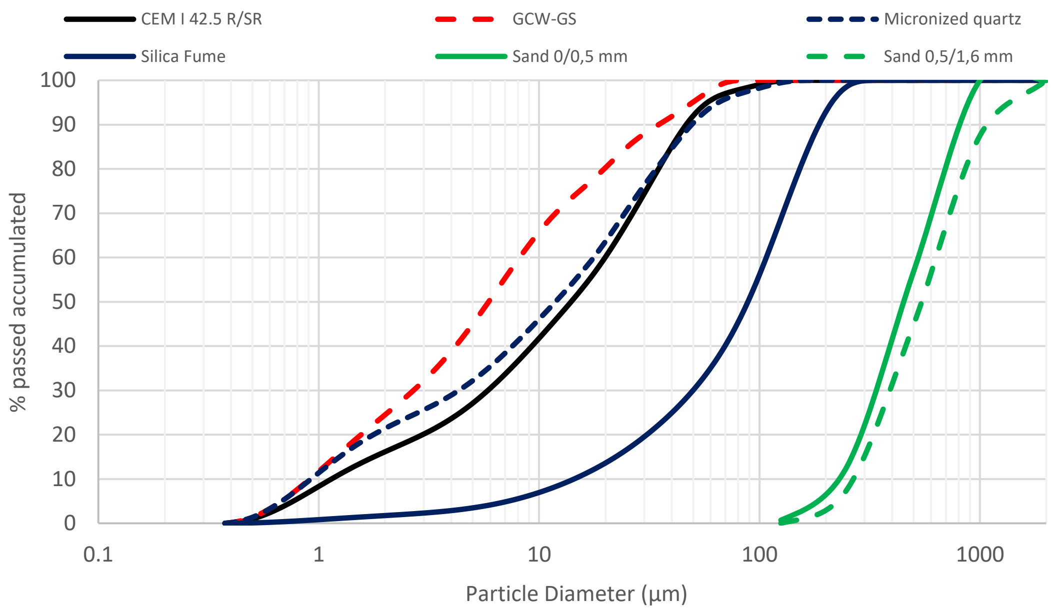

Figure 2. Granulometric curves of materials.

The granulometric curve resulting from the combination of all the components of the concrete mixtures with the different substitutions of GCW-GS is shown in Figure 3. As the percentage of substitution rises, there is a slight improvement in the granulometric distribution, following the criteria of ideal packing curves proposed by authors such as Andreasen or Funk and Dinger [20]. It therefore follows that the influence of the granulometry on the final result will be a slight improvement in the packing.

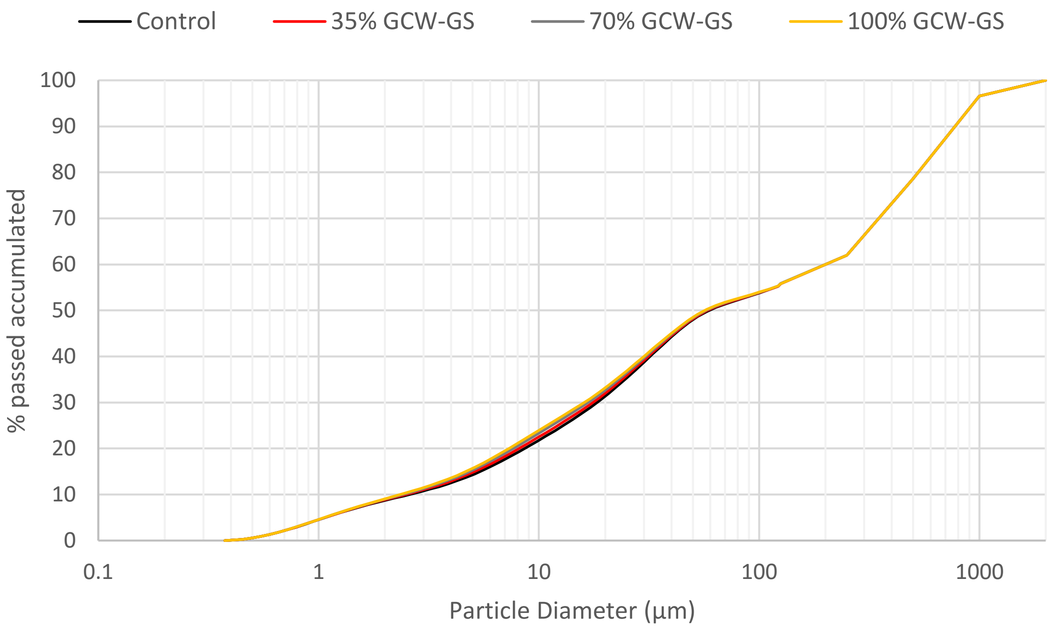

Figure 3. Granulometric curves of the mix for different percentages of substitution with GCW-GS

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2.2 Mix design

To carry out this study, the mix proportions of the UHPFRC were controlled until achieving a self-compacting control UHPFRC with a compressive strength above 110 MPa. Once the control dosage was established, the experimental program continued, substituting 35%, 70% and 100% of the micronized quartz for the same volume of granite cutting waste (GCW-GS). Table 4 shows the dosages of the resulting UHPFRCs. The higher the percentage of GCW-GS substitution, the more superplasticizer additive, (SP), was necessary. This is due to the reaction of the water with the CaO present in this waste, which dehydrates the mixture.

Table 4. Mix proportions of ultra-high performance steel fibre reinforced concrete (UHPFRC) (kg/m3).

Specimen	Cement	Sand 0/0.5	Sand 0.5/1.6	Micronized quartz	Granite sludge powder	Silica fume	Water	SP	Steel fibres
Control	800	302	565	225	-	175	175	10	160
35% GCW-GS	800	302	565	146	79	175	175	15	160
70% GCW-GS	800	302	565	68	158	175	175	16	160
100% GCW-GS	800	302	565	-	225	175	175	18	160

2.3. Experimental program

The experimental program includes a total of four mixes. The first mix is the control UHPFRC and the other three are UHPFRC with GCW-GS in different percentages.

The mixing procedure was as follows: first, the silica sands and the micronized quartz or the corresponding granite waste were put in the mixer. Next, the silica fume and cement were added. The materials were mixed for 30 s before including the water. After two and a half minutes from the beginning of the mixing, the superplasticizer and the steel fibres were added. The mixing process ended after 25 min.

The specimens were manufactured according to the specifications of the UNE-EN 12390-1 standard [21]. A total of nine specimens were manufactured per mix: three prismatic specimens of 10×10×40 cm, three cubic specimens of 10×10×10 cm and three cylindrical specimens of 15×30 cm. The specimens were removed from the molds after 24 hours and transferred to a humid chamber where they remained for 28 days at a temperature of 20ºC and a relative humidity of 95%, as specified in the UNE-EN 12390-2 standard [22].

The following properties were evaluated: consistency of the fresh mix, density of hardened concrete, compressive strength, modulus of elasticity, flexural strength, and tensile strength.

2.3.1 Physical properties

The consistency of the fresh UHPFRC was determined once the mixing process was finished and according to the NF P 18-470 standard [23].

The density of the hardened UHPFRC was calculated following the specifications of the UNE-EN 12390-7 standard [25]. This was done using the three 15×30 cm cylindrical specimens cast per mix.

The compressive strength was determined using the three cubic specimens of 10×10×10 cm, following the indications of the UNE-EN 12390-3 standard [26]. The modulus of elasticity was determined

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according to the UNE-EN 12390-13 standard [27] using the three 15×30 cm cylindrical specimens. The flexural strength and the tensile strength of the UHPFRC were calculated according to the NF P 18-470 standard [23] on the three prismatic specimens of 10×10×40 cm.

The tensile strength was determined by inverse analysis from the stress-strain curves obtained from the flexotraction test, following the methodology proposed by López Martínez in his doctoral thesis [28].

Table 5 shows the mean value of the results obtained from testing three specimens for each percentage of substitution.

Table 5. Average results of UHPFRC.

Properties	Control	GCW-GS		
		35%	70%	100%
Slump (cm)	25.0	23.0	20.0	21.0
Density (kg/m3)	2410.0	2420.0	2470.0	2500.0
Compressive strength (MPa)	117.2	127.3	133.8	128.8
Modulus of elasticity (GPa)	45.2	43.4	42.2	41.4
Flexural strength (MPa)	23.0	25.7	18.9	22.2
Tensile strength (MPa)	8.7	11.8	6.8	8.8

3. Analysis of results

As mentioned above, the particularity of the granite wastes from gang saws used in this test, (GCW-GS), is that they contain higher percentages of CaO (4.5%) and Fe2O3 (14.6%) than the granite cutting waste from diamond saws (GCW-D) [16]. Therefore, the results obtained will be related, in some way, to the presence of these compounds in the manufactured concrete.

Both CaO and Fe_2O_3 are occasionally used as additives in form of nanoparticles to change the properties of mortars and concretes. For this reason, to facilitate the analysis of results, the percentage increase of Fe_2O_3 and CaO with respect to the amount of cement used in the different mixtures has been calculated (Table 6). The use of GCW-GS in substitutions of 35%, 70% and 100% is equivalent to the addition of 1.43%, 2.88% and 4.1% of Fe2O3; and of 0.44%, 0.88% and 1.26% of CaO, respectively, in relation to the amount of cement in the mix.

Table 6. Percentage of Fe_2O_3 and CaO relative to the amount of cement in the mix

Specimen	Cement (Kg/m3)	GCW-GS (Kg/m3)	Fe2O3 (14,6% GCW-GS) (Kg/m3)	CaO (4,5% GCW-GS) (Kg/m3)	% Fe_2O_3 over cement	% CaO over cement
Control	800	-	-	-	-	-
35% GCW-GS	800	79	11,5	3,55	1,43 %	0,44 %
70% GCW-GS	800	158	23,06	7,11	2,88 %	0,88 %
100% GCW-GS	800	225	32,85	10,12	4,1 %	1,26 %

Iron oxide (Fe_2O_3) is often used as an additive in mortar and concrete in percentages of up to 5% of the amount of cement because the pozzolanic reactions it causes improve the mechanical strength. [29–32].

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Calcium oxide (CaO) is also used as an additive in mortars and concretes in percentages of up to 5% to reduce shrinkage without adverse effects on compressive strength in high-performance concrete. This is due to its pozzolanic effect when used in combination with silica fume [33].

3.1. Workability

The results obtained for consistency are shown graphically in Figure 5 together with those obtained in the previous article [16] for GCW-D wastes. Very different behaviour is observed with the two different granite wastes. The consistency of fresh UHPFRC increases when GCW-D is used as an alternative to micronized quartz, while GCW-GS produces a loss in the consistency. The inferior workability of the mix with GCW-GS is most likely due to the dehydration effect produced by the presence of CaO in the mix. Although to some degree it is compensated for by adding superplasticizer, its effect is still evident.

The loss of workability for UHPFRC with GCW-GS when increasing the percentage of substitution concurs with the results obtained in other studies when incorporating waste of granite stone slurry as an alternative to the finest aggregate [6].

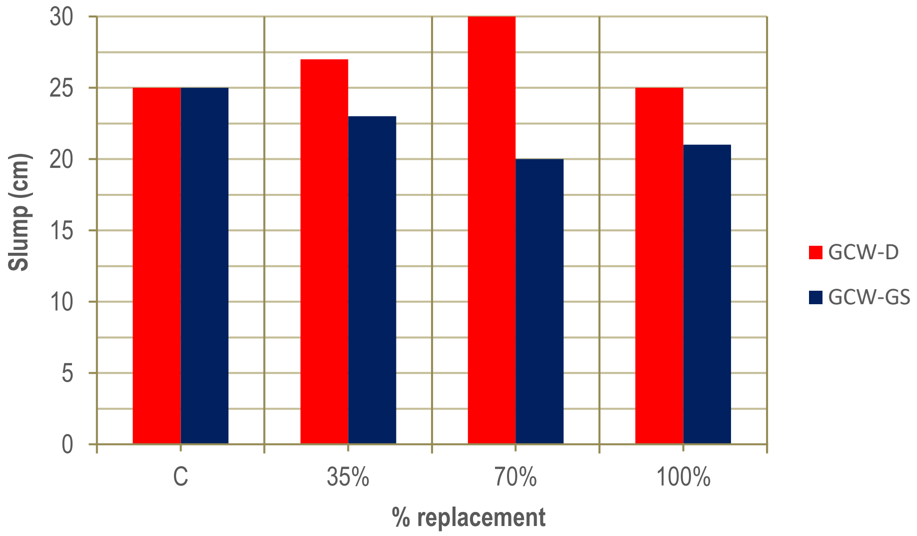

Figure 5. Slump of UHPFRC.

3.2. Density

Figure 6 shows the average results obtained from the density tests on the different mixes of hardened UHPFRC. The results show a higher density for the mixes with GCW-GS and an increase in density as the percentage of substitution increases. This is due to the higher particle density of GCW-GS, 2856 kg/m3, compared to micronized quartz, 2609 kg/m3. In the case of UHPFRC with GCW-D, although a reduction in density is observed, the variation is less than 2% and is within the error bars (Figure 6). In summary, the incorporation of GCW-GS produces an increase in the density of the concrete while the incorporation of the residue GCW-D does not affect this property.

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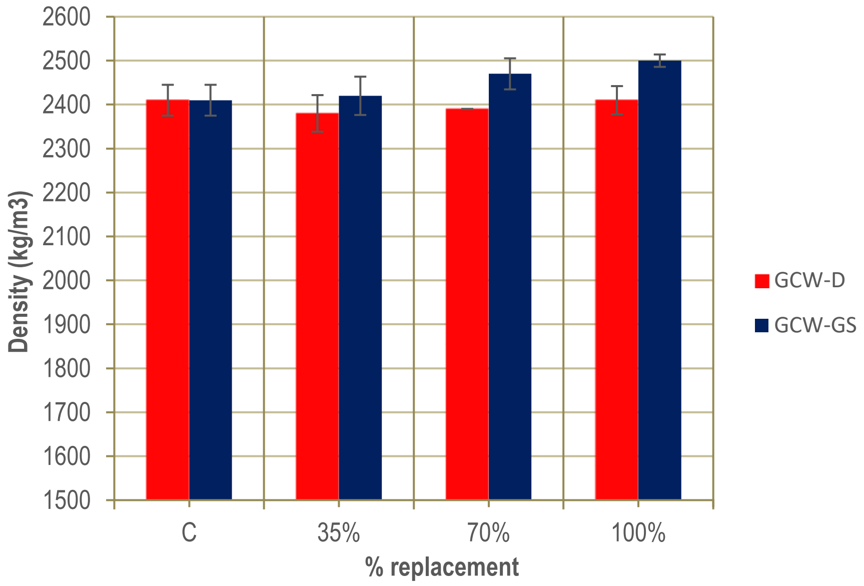

Figure 6. Density of UHPFRC.

3.3. Compressive strength

Figure 7 shows the results obtained. They correspond to the mean values obtained in the tests for each mix. In the first place, an increase in compressive strength can be seen for the different substitution percentages, regardless of the type of waste. The results obtained are above 120 MPa, reaching a compressive strength of 133.8 MPa for 70% GCW-GS. The strength of concrete with GCW-GS is around 5% better than concrete made with GCW-D. There are two factors that can explain this improvement. Firstly, there is a slight improvement in packing produced by GCW-GS, as can be seen in the granulometric curves in Figure 3. Secondly, the presence of Fe_2O_3 and CaO in the mixture improves pozzolanic activity [29],[30],[31],[32] and reduces autogenous shrinkage [33]. The favourable effect of Fe_2O_3 occurs for substitution percentages of around 2-3% on the total quantity of cement [31],[34]. This explains the slight decrease in compressive strength for the 100% substitution with GCW-GS (equivalent to 4% of Fe_2O_3).

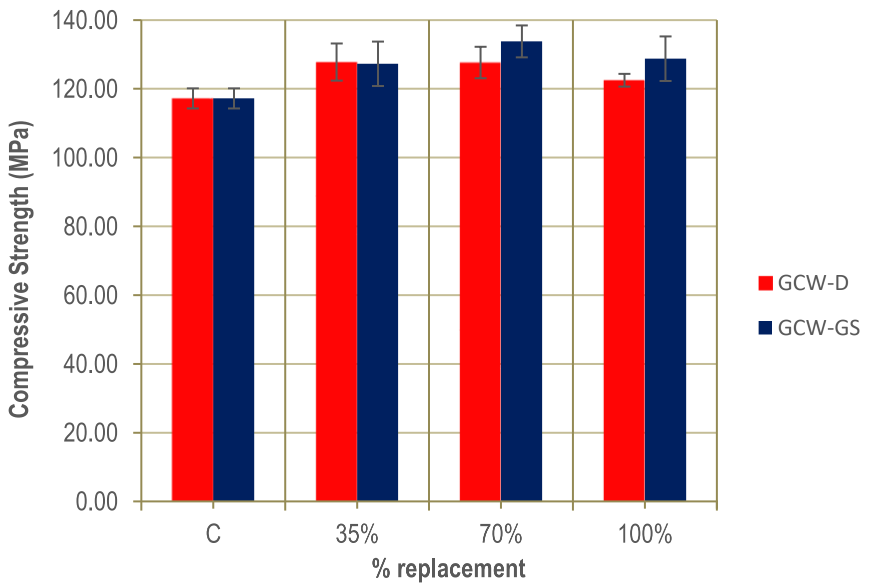

Figure 7. Compressive strength of UHPFRC.

These increases in compressive strength are similar to the results obtained in other studies where granite wastes were used in the manufacture of different types of concrete [3],[5],[16].

3.4. Elasticity modulus

Figure 8 shows the mean values of the elasticity modulus for the different mixes as a function of the percentage of substitution and the type of waste (GCW-D or GCW-GS). The results for the GCW-GS show a slight decrease in the modulus of elasticity with respect to the control concrete. For concrete with GCW-D the variations are negligible, 3% for a substitution of 100% GCW-D. In the case of GCW-GS, a greater reduction in the modulus of elasticity is observed, between 3.5% and 8.5%, depending on the percentage of substitution.

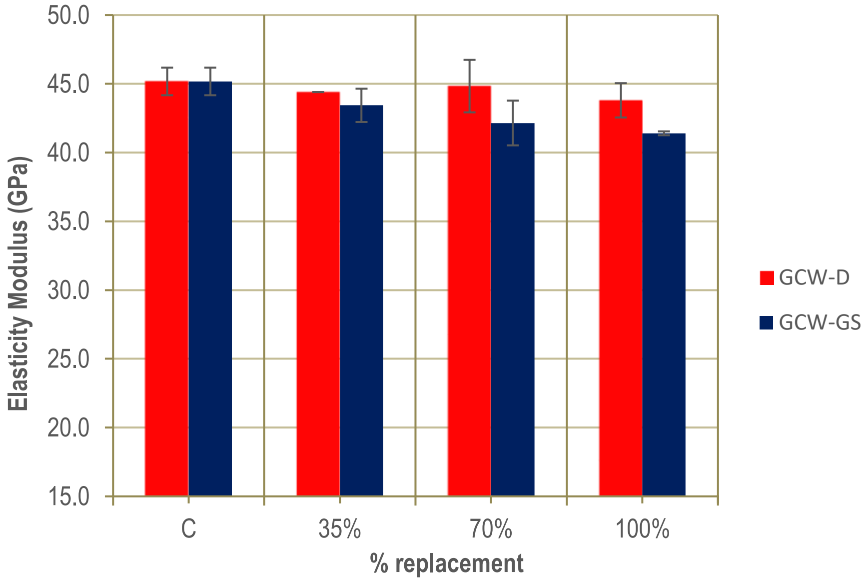

Figure 8. Elasticity modulus of UHPFRC.

Overall, the modulus of elasticity tends to decrease with most of the substitute materials used in the studies discussed below. Pyo and H. K. Kim [35] did not observe significant variations in the modulus of elasticity of concrete when incorporating different types of ash as an alternative to silica powder. For a ratio of 25% fly ash, the variation is less than 6.5%. J. Suárez et al. [15] also observed a slight variation when incorporating waste mining sand (WMS) as an alternative to the finest silica sand. For a replacement of 100% WMS, the loss is less than 6%. However, in other studies the results show more significant variations. Yacizi et al. [36] analysed the influence of using blast furnace slag and fly ash on the properties of reactive powder concrete. A decrease in the modulus of elasticity of 10% and 18% respectively were observed when 30% and 40% of blast furnace slag was incorporated. However, Safiuddin et al. [37] observed an increase of between 2% and 3% in the modulus of elasticity of High Performance Concrete when using industrial by-products. This was related to a reduction in its porosity.

3.5. Flexural strength

Figure 9 shows the effects of granite wastes on the flexural strength of UHPFRC. The high variability in the results may be due to the fact that the steel fibres are not evenly distributed in the matrix. For a substitution of micronized quartz of 35%, a slight increase in flexural strength is observed over the control concrete with both types of wastes. For 35% GCW-D this increase is 6%, while for 35% GCW-GS it is 12%. However, for higher percentages of substitution, a decreasing trend in flexural strength is observed. As with compressive strength, the presence of Fe2O3 in percentages greater than 2-3% of the total cement (equivalent to a 70-100% substitution with GCW-GS) is the cause of the loss of strength. In any case, all the results are in a range of values close to those of the control concrete.

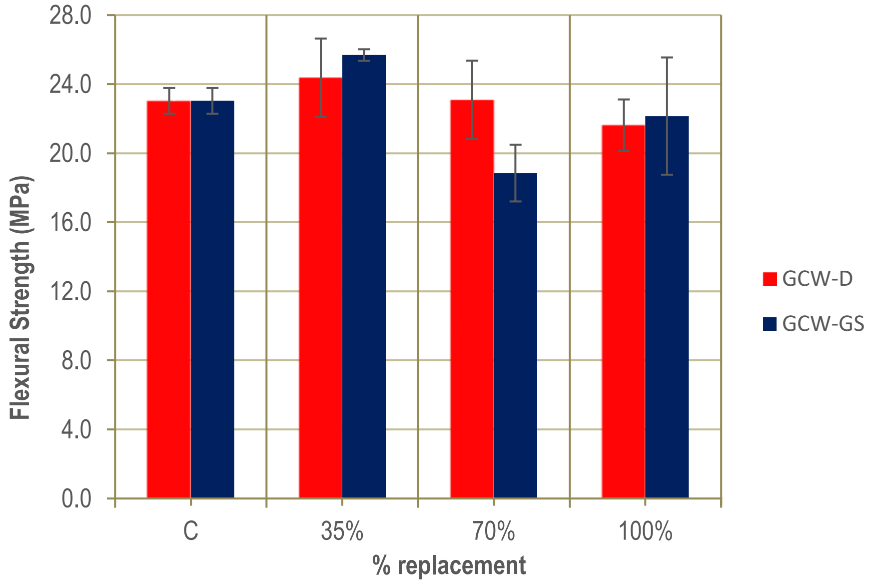

Figure 9. Flexural strength of UHPFRC

These results are similar to those obtained in the study carried out by S. Singh et al. [3].

3.6. Tensile strength

Figure 10 shows the mean values of tensile strength of UHPFRC. The results obtained replicate those obtained in the preceding test. For a ratio of 35% an increase in tensile strength is observed, reaching 10.8 MPa for GCW-D and 11.8 MPa for GCW-GS. These are increases of 24% for GCW-D and 35% for GCW-GS. However, for substitutions of 70% or more, the values obtained are similar to those of the control UHPFRC. Except for the 70% GCW-GS, where a loss of 22% is observed, the variations are less than 5% and are within the error bars of the test.

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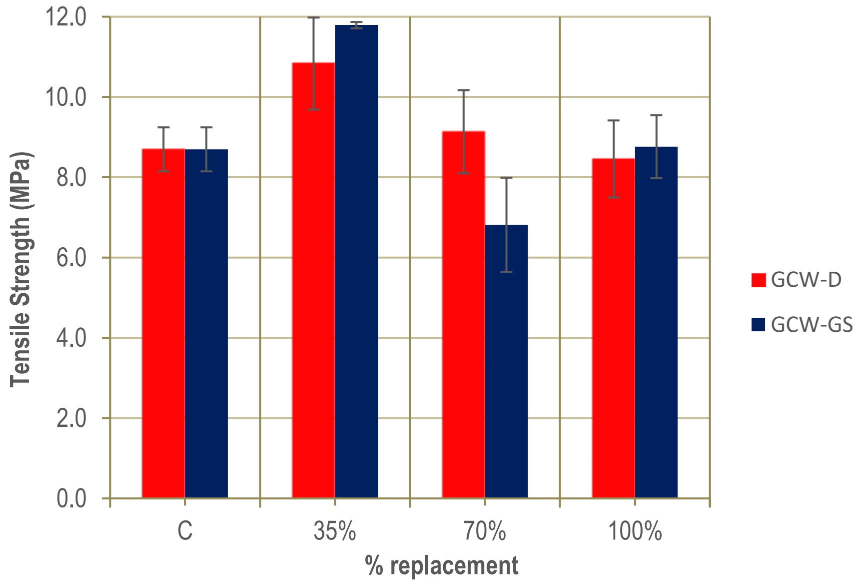

The presence of iron oxide explains both the improvement in results with 35% replacement and the deterioration for higher percentages of replacement, as mentioned in the section corresponding to the compression strength test.

These tensile strength results are similar to those obtained by Aldahdooh et al. [38].

4. Conclusions

In view of the results obtained, it can be concluded that the use of granite cutting fines waste is a viable alternative as partial substitutes for micronized quartz in the manufacture of Ultra-high Performance Fibre Reinforced Concrete (UHPFRC). When comparing the results obtained with granite cutting waste from gang saws (GCW-GS) with those obtained with granite waste from diamond saws (GCW-D), it can be concluded that the presence of Fe2O3 and CaO in the GCW-GS has a favourable impact on the properties analysed. The most relevant conclusions that have been obtained in this study are presented below:

- The incorporation of GCW-D increases the workability of fresh concrete, favouring the compactness of the mix. However, there is a loss of workability when incorporating GCW-GS, because of the CaO in the mixture, which increases the demand for water. This increase in water demand was foreseeable and was, to some degree, compensated for by increasing the amount of superplasticizer. However, it may be necessary to increase it further to achieve a more favourable result.

- The density of UHPFRC is influenced by the type of waste. Although the incorporation of GCW-D has no repercussions on the density of the concrete, with GCW-GS it rises as the percentage of substitution increases. This is due to the higher density of the iron oxide particles in the mixture.

- The compressive strength increases slightly for all the substitution percentages with the two types of waste used. This effect is more pronounced for the GCW-GS waste, with an increase of 14% for a 70% replacement. With the GCW-D waste this increase remains at 8.5% for the same percentage of substitution.

- The incorporation of granite cutting waste slightly decreases the modulus of elasticity of UHPFRC with both types of waste. This decrease is more pronounced for GCW-GS waste, 8% less for the100% replacement, than for GCW-D waste, 3% less for the same substitution.

- Regarding flexural strength, the results show high variability regardless of the waste used GCW-D or GCW-GS, or the percentage of substitution. The best results are obtained for a 35% substitution, where an increase of 12% is observed for the GCW-GS waste and 6% for the GCW-D with respect to the reference UHPFRC. The decrease in strength reaches 3.5% for the 100% replacement with GCW-GS and 6% for the same substitution of GCW-D.

- The results for tensile strength are very similar to those obtained for flexural strength. The best results are obtained with the 35% replacement, with an improvement of 35% using GCW-GS and 24% with GCW-D. For the 100% replacement, the values are practically the same as those of the control concrete with both types of waste.

- In general, the GCW-GS waste improves the results by an average of approximately 5% over the GCW-D waste. The exception is in the modulus of elasticity, where there was a loss of 5% as compared to the GCW-D waste.

- The final conclusion, based on the tests carried out, is that both GCW-GS and GCW-D can be used for the manufacture of UHPFRC with an improvement of all the properties up to a 35% replacement. From this percentage, the results remain at values close to the control concrete with no significant decreases, less than 10%, even for a 100% replacement.

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