

## Experimental Study on Tie Wire Fibre and Ceramic Wastes in Sand Concrete

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### ABSTRACT

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*sand concrete, ceramic waste, tie wire fibers, mechanical and physical properties, durability, compressive strength*

This study examines the use of recycled steel fibres obtained from reinforced wire debris and ceramic demolition waste in sand concrete. The research aims to assess the influence of these factors on the mechanical and physical properties of concrete while concurrently promoting environmental sustainability and fostering eco-friendly building techniques. The inquiry is divided into two main stages. In the first phase, recycled steel fibres derived from tying wire waste were included in ordinary sand concrete at varied proportions of 0.4%, 0.8%, 1.2%, 1.6%, and 2%. Tests performed on both fresh and hardened concrete, in addition to durability assessments. Results indicated that the use of 1.2% steel significantly improved the compressive strength by 38% and flexural strength by 66% at 28 days. The second phase examines the effect of replacing dune sand with ceramic waste sand (CWS) in the most promising fibre-reinforced concrete mix from the first phase (1.2% fibre content). CWS is used at replacement levels of 10%, 15%, and 20%. Results demonstrate that a 20% substitution significantly enhanced compressive and flexural strength by another 38%, and 10% respectively at 28 days. Furthermore, durability evaluations indicate that increased CWS content improves resistance to chemical degradation, underscoring its viability as an environmentally sustainable substitute for natural aggregates.

## 1. INTRODUCTION

Fibre-reinforced concrete is a composite material combining a matrix and a reinforcement [1]. One of the most common roles for fibres is to reduce concrete cracking, caused by shrinkage and thermal variations, among other factors. In recent years, the applications of fibre-reinforced concrete have significantly expanded globally. It is used in the manufacture of constructions, roads, urban development, and civil engineering [2]. However, despite its many advantages, fibre-reinforced concrete is not yet used on a large scale throughout the world due to a number of factors: it is more expensive than conventional concrete because of the cost of the fibres and their processing, especially when metal or special fibres are used; the long-term effects of the fibres, particularly in aggressive environments, are not always well understood, which may give rise to concerns about their durability [3]. To partly address this situation, this study explores using tie wire scraps and recycled ceramic sand in concrete. This combination of the two wastes can contribute, on the one hand, to reducing production costs and, on the other hand, to protecting the environment and conserving natural resources.

First, construction sites widely use tie wire to secure ironwork. People also refer to it as soft steel wire. Recruits give it the flexibility and softness necessary for its primary use. The connection wire, or attachment wire, is available in a variety of diameters ranging from 0.61 mm to 1.22 mm.

Plasticised raw iron composes it, giving it the ability to oxidise and break down after approximately one year, depending on climate conditions. It then falls and degrades naturally [4]. There is relatively little literature on the application of attachment wire drops as fibres in the concrete field; however, established studies on the effect of soft steel fibres show encouraging results in terms of their ability to improve concrete's mechanical performance and durability.

For example, Laid et al. [5] incorporated tie-wire fibres into ordinary concrete at concentrations of 0.5% and 1%, using lengths of 20 and 50 mm. They observed that the shrinkage decreased with increasing levels of tie wire fibres. In 90 days, the shrinkage decreased from 14% to 19% for the fibres with a length of 20 mm in the 0.5% and 1% mixes, respectively. On the other hand, when they used different lengths of 50 mm, they observed a decrease in shrinkage from approximately 22% to 37% for both fibre proportions of 0.5% and 1% after 90 days. He reported that the slenderness of these fibres (L/D) could explain this decrease. However, Figueiredo and Ceccato [6] conducted a study on the rheological properties of reinforced concrete using steel fibres (commercialised fibre) measuring 60 mm long. They observed a decrease in slump as the fibre volume fraction increased, demonstrating the significant influence of steel fibres on concrete mobility. On the other hand, other studies have observed a significant improvement in the compressive strength. Ammari et al. [7] reported that the incorporation of steel fibres (MEDAFAC

standardised fibres) with a length of 35 mm and an aspect ratio of 50 improved the compressive strength of sand concrete with barley straws by more than 11% and by more than 10% after the wetting-drying test. They reported that there was a slight decrease in the compressive strength after the wetting–drying cycles for all the studied concrete. Furthermore, Shewalul [8] conducted an investigation into the mechanical properties of concrete using various percentages (0, 0.5, 0.75, and 1.5%) of waste steel scrap, which were collected from the heavy manufacturing and machine building industry. Results showed that the addition of 0.75% of waste steel scarp increased compressive strength by 30.7% but reduced the workability of the concrete. The use of recycled aggregates in concrete is not a recent trend. What is new today is the use of a wide variety of waste materials from construction and deconstruction [9]. These include tiles, earthenware, brick, granite, glass, wood, and ceramic.

Ceramic is an inorganic, non-metallic material manufactured by firing natural substances at high temperatures. It is used in a variety of sectors, including construction and industry, because of its resistance to heat and wear and its durability. Its composition varies according to its use but generally includes clay, silica, alumina, limestone, metal oxides, and other minerals such as feldspar. Once fired, these components form a solid, durable material [10].

Several studies have explored the use of recycled ceramic sand in reinforced sand concrete, detailing its definition, manufacturing process, and chemical properties [11].

Olarinoye et al. [12] investigated the impact of partially substituting sand as fine aggregates with ceramic waste tiles at varying percentages (0, 5, 10, 15, 20, and 25%) on the density, compressive strength, and radiation shielding competency of ordinary concrete. They found that the incorporation of 15% of ceramic waste tile improved the dry density and compressive strength, making the concrete more effective at radiation absorption when used in shielding applications in medical and other radiation facilities.

Moreover, Mhadhbi [13] conducted a study on the use of recycled sand from ceramic waste tile in the formulation of flowable sand concrete (FSC). They substituted 0, 5, 10, 15, 20, and 25% of conventional sand with ceramic waste sand and then examined the properties of both fresh and hardened concrete. They found that adding 25% ceramic waste sand reduced the workability and improved the mechanical strengths of FSC.

Furthermore, Samadi et al. [14] conducted research investigating the use of ceramic waste as a partial substitute for cement and fine aggregates in new mortars. The researcher uses various methods to characterise the mixture, including scanning electron microscopy (SEM), thermogravimetric analysis (TGA), differential thermal analysis (DTA), X-ray diffraction (XRD), and Fourier transform infrared spectroscopy (FTIR) measurements. They found that ceramic

waste enhances the compressive strength of the mortar and provides higher resistance against adverse environmental conditions. The beneficial interaction between ceramic waste and fine aggregates reduces porosity and cracking, hence improving performance and potentially leading to lower construction costs and increased sustainability.

The aim of this research is to examine the effect of incorporating increasing proportions of oxidizable steel tie-wire fibres, ranging from 0.4% to 2%, on selected properties of sandcrete. This first phase will help determine the optimal fibre content before proceeding to the second phase, which will focus on the partial replacement of dune sand (DS) with recycled ceramic waste sand at varied proportions of 0%, 10%, 15%, and 20%. The aim is to evaluate differences in mechanical performance and durability of reinforced sand concrete containing ceramic waste, in order to identify the most effective substitute for natural sand.

## 2. EXPERIMENTAL PROGRAM

The following sections provide information on the used materials in the study, as well as the experimental work done to achieve the research objectives.

### 2.1 Materials used

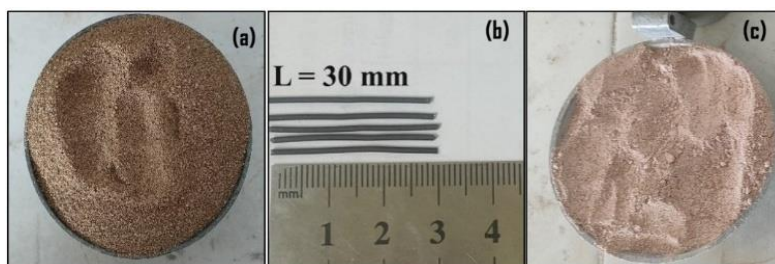
The binding phase is prepared using the following materials:

A Portland cement (C) of the CPA-CEM I /42.5N type, has an absolute density of 3.05 g/cm<sup>3</sup> and a specific surface area of 3290 cm<sup>2</sup>/g. This cement was provided by the company LAFARGE in Algeria. The chemical composition of the cement is shown in Table 1.

The limestone filler (LS) has an absolute density of 2.71 g/cm<sup>3</sup> and a specific surface area of 3900 cm<sup>2</sup>/g, respectively. This limestone filler was provided by the private company SFDM in Constantine, Algeria. The chemical composition of the limestone filler is shown in Table 1.

Two types of sand were used as fine aggregate: siliceous DS of class 0/1 (rolled nature) comes from Oued Zhor (Skikda-East of Algeria); it is presented in (Figure 1(a)), and ceramic waste sand (CWS) of class 0/4. Ceramic waste is mechanically crushed to produce sand. First, large recovered ceramic pieces are broken into smaller fragments. These smaller pieces are then further crushed using a crusher and passed through a 4 mm sieve to achieve the desired grain size.

The tie waste fibre (TWF) used in this study (Figure 1(b)) has a length of 30 mm and a diameter of 1.05 mm, resulting in an aspect ratio of 28. Its density is 7850 kg/m<sup>3</sup>, and it exhibits a tensile strength of 206 MPa. These fibres were recovered at construction sites.



**Figure 1.** Materials (a) Dune sand (DS), (b) tie wire fibers, (c) ceramic waste sand (CWS)

In addition, the ceramic waste sand was used in dry condition and no pre-wetting procedure was applied prior to mixing. The resulting fine ceramic sand (Figure 1(c)). Tables 1 and 2, respectively, group the chemical and physical properties of the various types of sand.

A superplasticizer/high water reducer (Sika ViscoCrete 665) has a 32±1.2% dry extract, with a dosage range of 0.3 to 3.0% of the binder weight and tap water (E) for mixing.

## 2.2 Characterization of materials

### 2.2.1 Chemical characteristics of cement and fine aggregates

The chemical composition of cement, including LS, DS, and CS was analysed using gravimetric techniques as specified in IS:1727-1967, as shown in Table 1.

**Table 1.** Chemical properties of materials used

Oxydes	Chemical Composition (%)			
	C	LS	DS	CWS
SiO <sub>2</sub>	23.30	0.13	94.26	74.96
Al <sub>2</sub> O <sub>3</sub>	4.57	0.02	2.38	17.3
Fe <sub>2</sub> O <sub>3</sub>	5.50	0.02	1.13	1.75
CaO	62.08	55.77	0.82	1.46
MgO	1.79	0.20	0.15	0.24
SO <sub>3</sub>	1.70	/	0.01	0.07
K <sub>2</sub> O	0.10	/	0.22	2.20
Na <sub>2</sub> O	0.16	0.01	0.19	1.52

Note: LS: limestone filler; DS: dune sand; CWS: ceramic waste sand

### 2.2.2 Physical properties of sands used

The physical properties of DS and CWS are shown in Table 2.

From Table 2, it can be seen that:

1. The absolute density of CWS (2.64 g/cm<sup>3</sup>) is slightly higher than that of DS (2.61 g/cm<sup>3</sup>), indicating that ceramic waste sand has a denser internal structure. Although the difference is minimal, it could slightly influence the overall density of the concrete mix.

2. CWS has a much higher filler content compared to DS. These fillers could be beneficial in some cases by improving the particle packing and reducing voids but may also increase the water demand and reduce workability.
3. CWS has a very high-water absorption compared to DS. This is likely due to the porous nature of ceramic sand.
4. CWS has a lower sand equivalent than DS, which is considered extremely clean sand. For this purpose, we consider sand resulting from waste ceramic to be as clean and acceptable to use in concrete.
5. An old mortar that has adhered to the grain surface explains why ceramic waste sand has a higher absorption coefficient than dune sands [15].

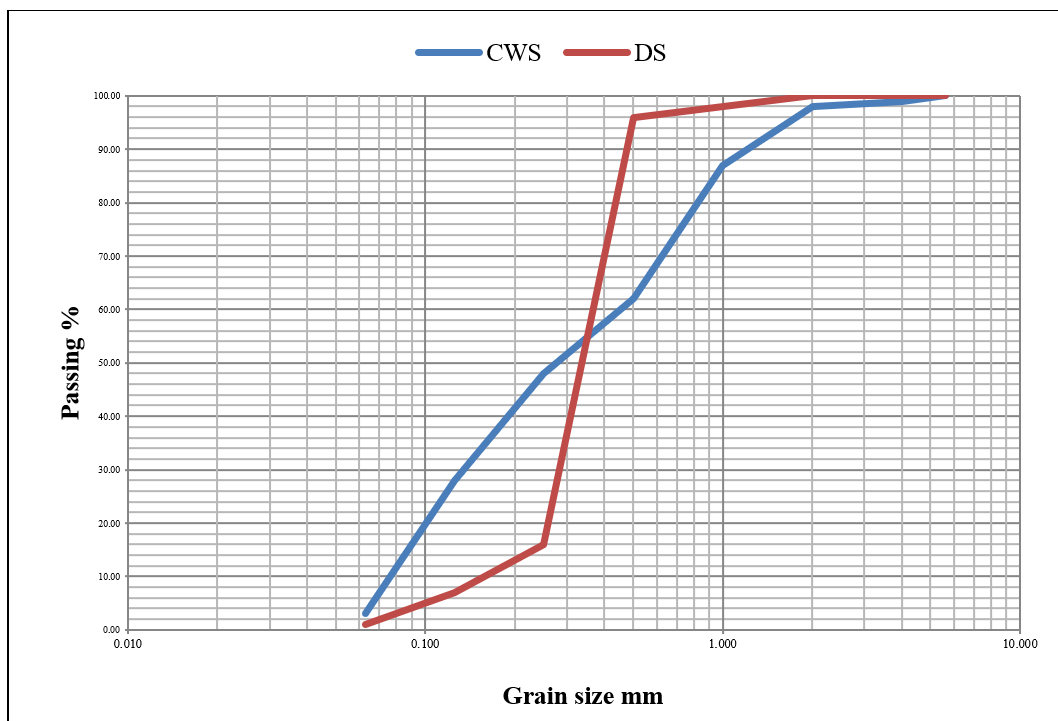
According to British Standard EN 12620:2002+A1:2008 [16] the fines content = 14.81% it was an acceptable of aggregates used in concrete, especially with another condition complementary which is the sand equivalent = 65%, which generally indicates an acceptable cleanliness for concrete aggregates.

**Table 2.** Physical properties of sands

	Physical Properties		
	DS	CWS	Standard
Bulk density (g/cm <sup>3</sup> )	1.500	1.288	EN 1097-3
Density (g/cm <sup>3</sup> )	2.610	2.640	EN 1097-6
Sand equivalent (%)	80	65	NF EN 933-8
Water absorption (%)	0.29	5.10	EN 1097-6
Fineness modulus (%)	1.89	1.68	EN 933-1
Fines content (%)	1.53	14.81	EN 933-1

### 2.2.3 Particle size analyses

From Figure 2, it can be seen that sands are well graded, with a maximum size of 2 mm for waste ceramic sand and 1mm for DS. Ceramic waste sand has a dispersed grain size, while DS has a tight grain size.



**Figure 2.** Particle size distribution of sands used

### 2.3 Mix proportions and specimens' preparation

The investigation program aims to evaluate the impact of ceramic waste sand on the performance of reinforced sand concrete bases, which are made of steel waste fiber (tie wire). We accomplish this study by conducting a comparative analysis between the blended mixes and the conventional concrete. We determined the control mix (C0) design using the experimental approach from the SABLOCRETE [17] project. We formulated it to achieve a compressive strength of 25 MPa and a slump test equal to 170 mm, using a W/C ratio of 0.59. Then, we prepared fiber-reinforced concrete (CF) by substituting waste fiber ties at percentages of 0.4, 0.8, 1.2, 1.6, and 2% for the volume of DS. The study will evaluate the physical and the mechanical qualities of the concrete mixes, both in the fresh and hardened states, as well as their durability characteristics. At the end of this phase, we chose the best-

performing of the fiber-reinforced concretes for the rest of the study. After that, we prepared ceramic-reinforced concrete (RC) by making another volumetric substitution of DS with waste sands of ceramic at percentages of 10%, 15%, and 20%. We then conduct tests in both the fresh and hardened states, as well as durability tests, and select the most effective sand waste and its percentage that enhances our control concrete. We gathered and cured sand concrete specimens according to the NF EN 12390-1 standard method. Cast specimens were demolded after 24 hours and cured in laboratory conditions ( $T = 20 \pm 2 \text{ }^\circ\text{C}$ ) until the testing ages.

The notation and the mixtures compositions used are mentioned in Table 3 as follows:

C0: Sand concrete control.

CF: Reinforced sand concrete.

RC: Ceramic reinforced sand concrete.

**Table 3.** Mix proportions of different concrete mixtures (kg/m<sup>3</sup>)

	Substitution Rate (%)	DS	TWF	W	C	LS	SP	CWS
C0	0% TWF	1277	0	265.5	450	150	3.6	0
CF1	0.4% TWF	1266.56	31.6	265.5	450	150	3.6	0
CF2	0.8% TWF	1256.12	63.2	265.5	450	150	3.6	0
CF3	1.2% TWF	1245.68	94.8	265.5	450	150	3.6	0
CF4	1.6% TWF	1235.24	126.4	265.5	450	150	3.6	0
CF5	2% TWF	1224.80	158	265.5	450	150	3.6	0
RC10	Best TWF rate: +10% CWS	/	/	265.5	450	150	3.6	/
RC15	Best TWF rate: +15% CWS	/	/	265.5	450	150	3.6	/
RC20	Best TWF rate: +20% CWS	/	/	265.5	450	150	3.6	/

Note: LS: limestone filler; DS: dune sand; CWS: ceramic waste sand; TWF: tie waste fibre; SP: Superplasticizer

The tests that were carried out to analyse the behaviour of all the concretes are:

The workability of freshly developed concrete mixtures was assessed by measuring the slump using the Abrams cone test, in compliance with the NF EN 12350-2 standard. The air content of all fresh series of SC was assessed using a calibrated air content measurement in accordance with NF EN standard 12350-7. The fresh density was assessed post-casting in compliance with the NF EN 12350-6 standard.

The compressive strength test was performed at the ages of 3, 7, 28, and 90 days on cubes (150 × 150 × 150) mm<sup>3</sup> according to the standard NF EN 12390-3.

The flexural strength test was performed at the ages of 3, 7, 28, and 90 days on prisms (70 × 70 × 280) mm<sup>3</sup> according to the standard NF EN 12390-5.

Immersion absorption test was performed in accordance with Standard NF EN 12390-2:2001.

Following the Standard ASTM C 267-97, the resistance to chemical attack was evaluated using sulfuric acid (H<sub>2</sub>SO<sub>4</sub>) and hydrochloric acid (HCl) solutions, each prepared at a concentration of 5%. Cubic specimens of dimensions 70 × 70 × 70 mm<sup>3</sup> were first cured under laboratory conditions until the selected exposure age. After to curing, the specimens were immersed in acid solutions for durations of 7, 14, 21, 28, 56, 90, and 180 days. At each testing interval, the specimens were extracted from the solution, washed to remove loose reaction products from the surface, superficially dried, and weighed. The degradation resulting from acid exposure was evaluated based on % mass loss, determined relative to the specimen's starting mass prior to immersion. The acid solutions were kept at laboratory temperature during the whole exposure duration.

SEM analysis was operated by SEM: Quanta 650-FEI, USA. An acceleration voltage of 12.5–20 kV and a

magnification of 50-9008 were used. The observations were made both in secondary electrons and in backscattered electrons with image size 2048 × 1887 pixels.

### 3. RESULTS AND DISCUSSION

#### 3.1 Influence of tie-wire waste fibre on the properties of sand concrete

Table 4 clearly shows that the evolution of concrete slump as a function of fibre content is shown in Table 4, where an increase in slump is gradually observed as the fibre content increases. This corresponds to approximately 11.7%, 17.64% and 23.52% for fibre content levels of 0.4%, 0.8% and 1.2%, respectively. It was found that the minimum workability value was 17 cm for the control concrete (C0, 0% fibre). In contrast, the highest workability value was 22 cm for CF3 concrete with 1.2% fibre. This increase is caused by the fact that metal fibre does not absorb water, which leads to an increase in the amount of water and therefore an increase in the w/c ratio. In addition, the level of metal fibres does not reach a critical level that promotes greater contact between the fibre interfaces and disrupts the flow of concrete. These results contradict those obtained by the study [18]. Beyond a fibre content of 1.2%, a decrease in slump is observed as the fibre substitution rate increases, up to a value comparable to that of the control concrete. This can be explained by the destabilisation of the matrix due to the high fibre concentration, which leads to a decrease in workability. The research [19] obtained similar results.

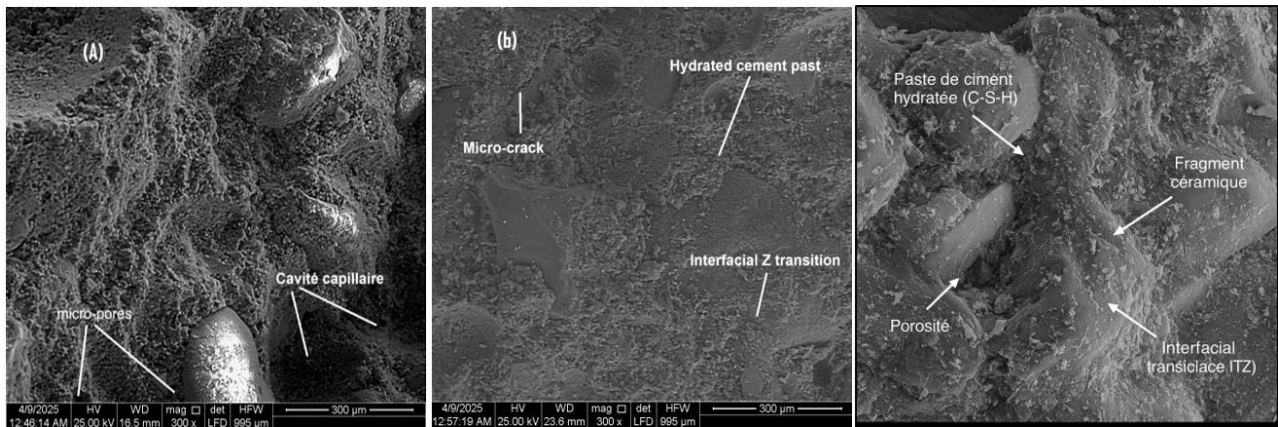
The density results for the different concretes, shows a relatively linear variation, with moderate increases at each

rate. This trend is to be expected, given that the fibers of waste binding wire, which have a higher density than sand (see Tables 2 and 3), contribute to increasing the mass of the

mixture [20]. Several researchers confirm that adding metal fibres significantly affects the density of fresh concrete [21, 22].

**Table 4.** Properties of reinforced concrete

Design	Fresh Properties						Hardened Properties					
	Slump flow (cm)		Density (g/cm <sup>3</sup> )		Air Content (%)		Compressive Strength at 28 Days (Mpa)		Flexural Strength at 28 Days (Mpa)		Absorption (%)	
	R	CV (%)	R	CV (%)	R	CV (%)	R	CV (%)	R	CV (%)	R	CV (%)
C0	17 ± 1	5,88	2.14 ± 0.01	0.47	3.9 ± 0.1	2.6	28.57 ± 0.06	0.21	5.36 ± 0.03	0.65	4.31 ± 0.03	0.8
CF1	19 ± 1	5.26	2.16 ± 0.02	0.93	4.1 ± 0.2	4.9	29.83 ± 0.02	0.06	7.13 ± 0.04	0.61	5.62 ± 0.06	1.0
CF2	20 ± 1	5.00	2.18 ± 0.01	0.46	4.4 ± 0.0	0	31.00 ± 0.11	0.34	7.47 ± 0.03	0.40	6.01 ± 0.10	1.6
CF3	22 ± 1	4.55	2.21 ± 0.01	0.45	4.6 ± 0.1	2.2	39.51 ± 0.06	0.14	8.94 ± 0.01	0.11	6.55 ± 0.07	1.1
CF4	20 ± 0	0.00	2.23 ± 0.02	0.90	5 ± 0.2	4.0	28.85 ± 0.03	0.12	6.52 ± 0.04	0.55	6.91 ± 0.12	1.7
CF5	16.5 ± 0.5	3.03	2.25 ± 0.03	1.18	5.9 ± 0.4	6.1	27.55 ± 0.05	0.17	6.15 ± 0.03	0.43	7.28 ± 0.08	1.0



**Figure 3.** Scanning electron microscopy (SEM) image of concretes (a) C0, (b) CF3, (c) RC20

The results concerning the air content show that increasing the substitution rate of DS with metal fibres increases the air content value compared to the value obtained for the control concrete (3.9%). The maximum value is recorded for concrete containing 2% fibre. An increase of 5.12%, 12.82%, 17.94%, 28.20% and 51.28% are observed for concrete containing 0.4%, 0.8%, 1.2%, 1.6% and 2% metal fibres, respectively.

This increase is due to voids created by the irregular distribution of metal fibres in the cement matrix. In addition, the fibres form a skeleton in the concrete mix, which creates a significant air void in the fresh mix [23].

The compressive strengths of the different types of concrete clearly show that adding waste tie-wire fibers generally makes compressive strengths better. This is especially true for CF3, which has the highest strength. This suggests that a proportion of 1.2% of oxidizable steel fibers has a very positive impact. In fact, the addition of these fibers strengthens the concrete, mainly through their ability to limit crack propagation and improve adhesion between the various constituents of it. They increase the cohesion and stability of the matrix, enabling the concrete to better resist compressive forces [24]. However, above this level, as in the cases of CF4 and CF5, a reduction in compressive strength is observed. This indicates that an excess of fibers could adversely affect strength, probably by disturbing the compactness and homogeneity of the concrete

[25].

In term of flexural strength, the results obtained show that the addition of tie-wire waste fibers significantly improves the flexural strength of concrete up to a ratio of 1.2%, where the improvement is highest in CF3 concrete. The fibers help to limit crack propagation, distribute stress uniformly, and improve cohesion between the various components of the concrete [26]. However, above this ratio, a reduction in flexural tensile strength is observed. This occurs due to improper concrete compacting and uneven fiber distribution, resulting in a material that is less homogeneous and cohesive.

The variation in the water absorption coefficient by immersion reveals a continuous increase in absorption capacity, with a first notable peak between CS and CF1, followed by more moderate variations between CF2 and CF5. The incorporation of fibers into the internal structure of the concrete is responsible for this evolution. Indeed, the waste fibers of the tie wire help increase the porosity of the material and create pores that facilitate water penetration [27].

The most important discovery from the study is the low CV% value, which appears in all tests. The laboratory methods for mixing, casting, curing, and testing were performed with a high degree of precision and control. The high level of repeatability in the results makes the trends in the average values (e.g., strength increasing from C0 to CF3, then

decreasing for CF4 and CF5) highly reliable and not due to random experimentation.

Figure 3 mentioned SEM image of all concretes, Figure 3(a) shows an SEM image of the control sand concrete at high magnification. It reveals a relatively dense microstructure, characteristic of well-hydrated concrete. The cement paste appears well bonded to the fine aggregates, indicating that the material is well compacted. Hydration products can be seen, in particular calcium silicates hydrate (C-S-H), visible as amorphous masses or in sheets. The general morphology is heterogeneous, with distinct granular zones corresponding to grains of siliceous sand, some of which have a rounded, shiny appearance, typical of quartz. Around these grains, the matrix has a spongy, porous structure, representative of hydrated cement paste [28]. Although these structures contribute to the mechanical strength of the concrete, the visible porosity may constitute a preferential route for the penetration of aggressive agents, thus affecting its durability. An interfacial transition zone (ITZ) has also been identified around the largest aggregate grains. This zone, which is more porous than the surrounding paste, is known to be the weak point of ordinary concrete, likely to have a negative influence on mechanical strength and long-term durability [29]. The surface analysed revealed numerous pores of micrometric size, relatively evenly distributed. These pores play an important role in permeability and ionic diffusion properties, particularly in the face of carbonation or chloride penetration.

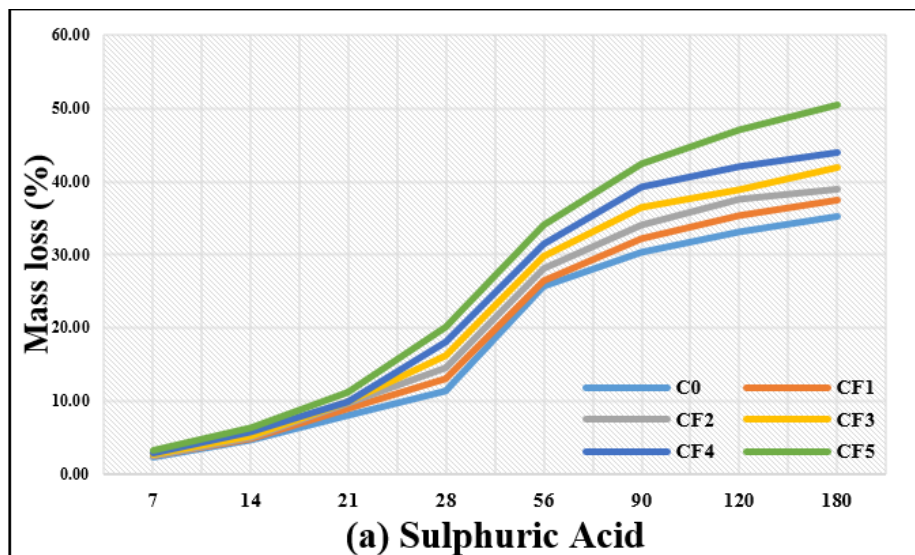
Finally, analysis of the distribution of equivalent diameters shows that most of the pores or particles detected have a diameter of between 5 and 50  $\mu\text{m}$ , corresponding to capillary and gel pores. A few coarser grains, up to 850  $\mu\text{m}$ , are also visible and probably correspond to well-coated fine aggregates. The dominant peak in the distribution confirms that the majority of features measured are micropores, directly influencing the transport properties of the material.

The SEM image CF3 (Figure 4) reveals several important features related to the incorporation of the tie wire fibres into the cementitious matrix. The metal fibres appear as elongated, shiny and distinct structures, distributed throughout the matrix. Their presence is well integrated, indicating a homogeneous distribution and good coating by the cement paste. This configuration is conducive to the mechanical effectiveness of the reinforcement, particularly in terms of controlling cracking [30]. Around the fibres, there is an ITZ,

which is sometimes slightly porous. This zone is crucial for adhesion between the fibre and the cementitious matrix. A compact ITZ favors stress transfer and limits delamination, while excessive porosity in this region could weaken fibre anchorage. The cement matrix has a structure typical of a well-hydrated cement paste, with spongy zones where hydration products develop, in particular C-S-H (hydrated calcium silicates). These play a fundamental role in the material's mechanical strength [31]. A few micrometric pores are also visible, mainly around the fibres and in certain areas of the matrix. These porosities have a direct influence on the permeability of the concrete and its sensitivity to external stresses, such as carbonation or chloride penetration. Overall, the SEM image (Figure 3(b)) shows that the metal fibres are well anchored in the cement paste and that their integration potentially improves the compactness and mechanical performance of the concrete [32]. This behaviour is particularly beneficial for concretes based on fine sand, such as DS, which are often less optimised in terms of granular structure. The addition of metal fibres therefore contributes effectively to strengthening the microstructure and improving the durability of the material.

With regard to resistance to chemical attack by sulfuric acid, Figure 4(a) illustrates that all the concretes tested achieved a gradual decrease in weight as their age increased, from 7 to 180 days. The weight losses of the concrete increase rapidly between 7 and 28 days; then this increase slows down after 56 days, although the overall trend remains increasing. At 180 days, CF1 concrete shows the weight loss closest to that of the control concrete. This decrease in strength can be attributed to the formation of new voids in the concrete, resulting in a less dense microstructure that is unable to effectively limit the penetration of sulfuric acid. This accelerates the degradative chemical reactions in the pores and cracks [33].

Figure 4(b) shows the results of testing the concrete's resistance to hydrochloric acid. It shows that all of the concretes lose mass over time, but the CF4 and CF5 concretes lose more mass than the others. This phenomenon could be due to a greater vulnerability of the concrete to hydrochloric acid attack due to several factors linked to the chemical reaction between the acid and the concrete components, increased porosity, zones of weakness created by the fibers, and direct degradation of the fibers themselves [34].



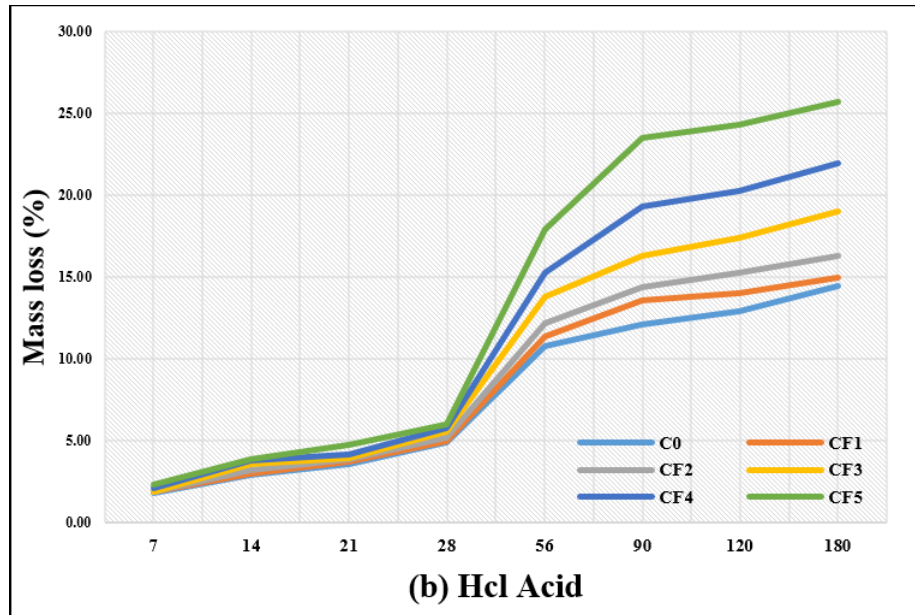


Figure 4. Mass loss of reinforced concrete (a) Sulphuric acid, (b) hydrochloric acid (HCl) acid

On the basis of the results obtained in this section, CF3 concrete was chosen for the rest of the study because of its excellent mechanical strength and satisfactory performance in terms of deformation and durability.

### 3.2 Influence of recycled sand from ceramic waste on the properties of sandcrete containing 1.2% fibres from waste tie wire

The following sections discuss the test results, focusing on the fresh properties, mechanical strengths, absorption capacity, microstructure and chemical attacks.

#### 3.2.1 Fresh state

Figure 5 presents the evolution of fresh state concrete as a function of the mass ratio of recycled ceramic sand. The results shown correspond to an average of the values obtained from three measurements.

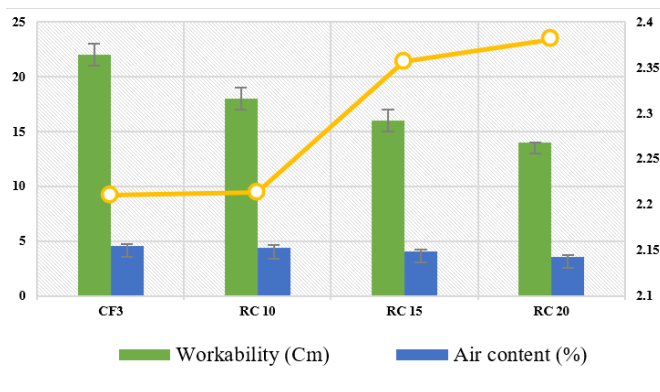


Figure 5. Variation in fresh properties as a function of substitution rate

All concretes show a decline in workability as the amount of CWS increases. The hardened old mortar, adhering to the initial grain of CWS, produces jagged surface characteristics, making the ceramic sand more rigorous than DS. This, in turn, increases friction between the grains and particles of the mixed sand, thereby reducing concrete slump [35]. In addition,

adding a larger quantity of CWS results in a stiffer concrete mixture due to its increased water absorption compared to DS, which in turn consumes a quantity of water necessary for the blending process. Neville and Brooks [36], Sivakumar et al. [37] noted a similar tendency when used as fine and coarse aggregates, construction and demolition waste (CDW) replaces conventional materials in concrete. The Standard Deviation of this test is very consistent, ranging from  $\pm 0.5$  cm to  $\pm 1$  cm and the CV% is low for all mixes (0% to 6.25%), confirming good workability control. RC 20 shows a CV of 0%, indicating the most consistent slump result in this set, which is theoretically perfect consistency, though a  $\pm 0$  value in practice might suggest the result was rounded.

The replacement of DS with CWS boosts the fresh densities of concrete mixtures, reaching the highest density in concrete that contains 20% CWS. Furthermore, it exceeds the value of ordinary concrete by 7.73%. This rise in density may be ascribed to the greater absolute density of CWS in comparison to DS (refer to Table 2). Furthermore, the finer particle size of CWS may enhance the cohesiveness within the concrete mixture by occupying the spaces between the sand and cement [38]. The Standard Deviation is Very small, between  $\pm 0.01$  and  $\pm 0.07$  g/cm<sup>3</sup> and all CV% values are exceptionally low (0.07% to 0.44%). This indicates that the mixing and casting procedures were highly consistent, producing specimens with near-identical densities.

The air content of all mixtures decreases proportionally with the rise of CWS. The concrete base with 20% CWS achieves the minimal value, which is 21% lower than the control concrete. The air content of concrete mostly relies on the shape of the waste sands and the binding capability associated with the quantity of fine particles present [39]. The high fines content in the CWS improves the particle packing in the mix, reducing void spaces and decreasing the entrapped air content [40]. These results contradict those obtained by Xiao et al. [41] on sand concrete including ceramic waste sand. The Standard Deviation Ranges from  $\pm 0.0$  to  $\pm 0.4$ %. This property shows the most variation, with CV% values up to 12.02% for RC 10. This is expected, as air content can be sensitive to mixing time, speed, and the presence of CWS. RC 15 shows the lowest CV, while RC 20, show higher but still acceptable variability

(7.29%).

### 3.2.2 Compressive strength

The findings result of compressive strength shown in Figure 6.

The compressive strength of concrete is a critical metric that determines a structural member's ability to support certain loads during service. The findings shown in Figure 6 represent the mean values obtained from three specimens.

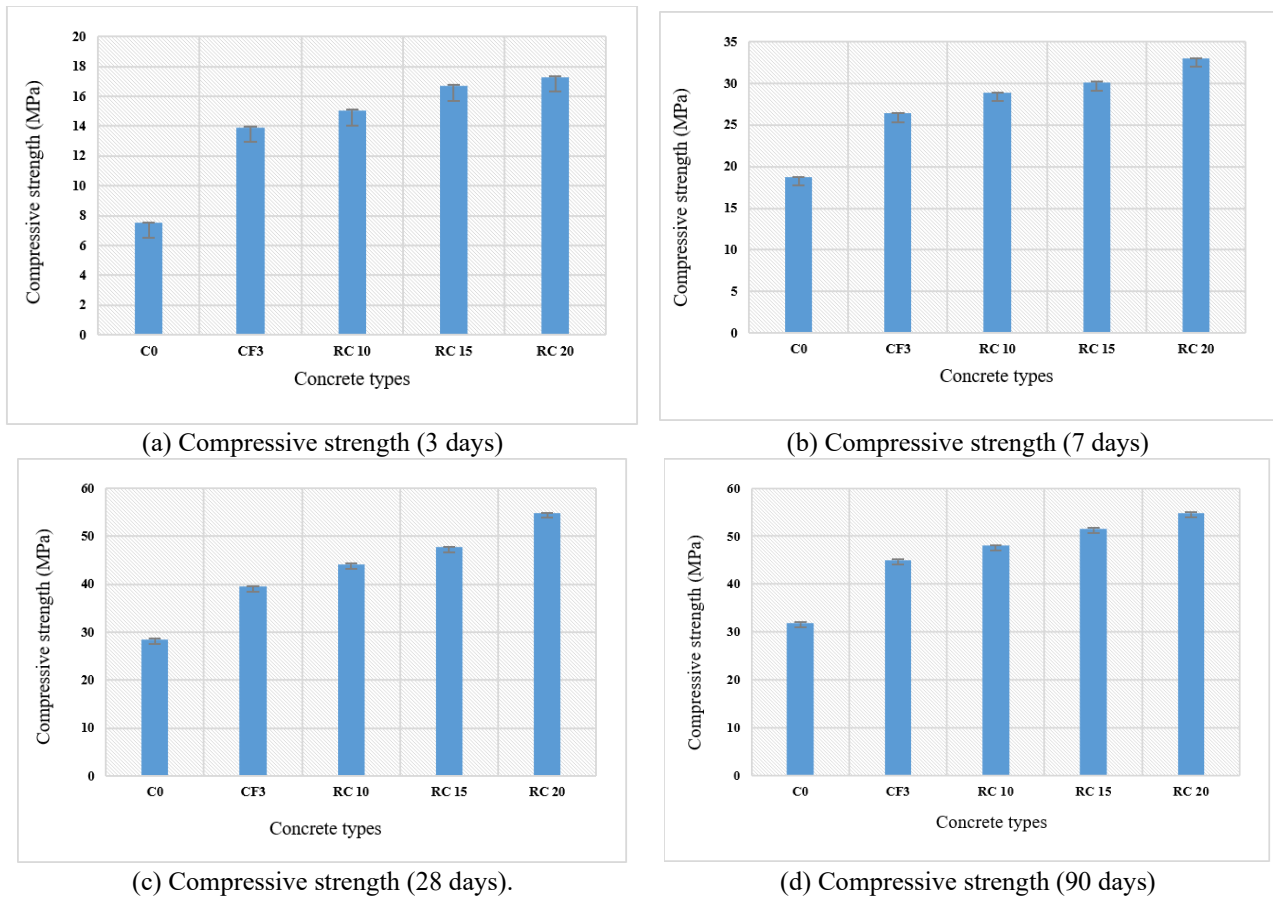


Figure 6. Variations of compressive strength of mix concretes

Initially, it was noted that the compressive strengths exhibit a tendency to improve throughout all curing times. This may be explained by the progression of the cement hydration process over time. Then, the compressive strength increases proportionately with the increased CWS replacement. The concrete with 20% CWS exhibited about a 36% and 21% increase in strength compared to CF 3 and about a 74% and 72% to C0 concrete at 28 days and 90 days, respectively. Previous research [42, 43] has shown comparable enhancements in compressive strength, which This enhancement in compressive strength is ascribed to some reasons: Ceramic waste has a higher absorption coefficient than DS, which is why the W/C ratio goes down. The fine particles of ceramic waste fill the spaces between the sand grains and stick together better with the cement paste. The existence of fine particles of unhydrated hardened cement in the mortar adhered to the grain of ceramic sand constitutes new nucleation sites, which accelerate the hydration reaction. In addition, there is better compatibility between the admixture and the fine particles of ceramic sand than with DS: the superplasticizer defloculates the grains and creates a favourable arrangement of the constituents in the cementitious matrix. Longer term, Awoyera et al. [44] found that the pozzolanic properties of ceramic waste microparticles make

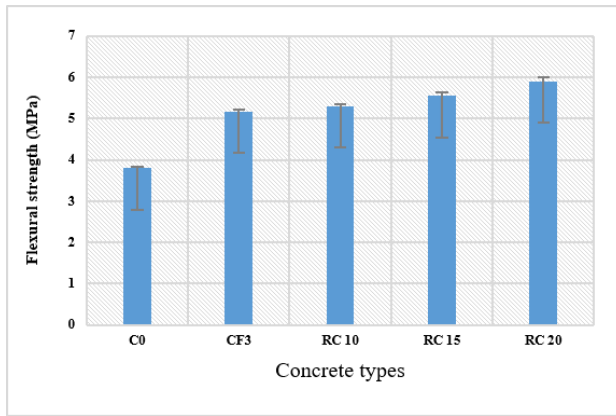
the compressive strength much higher after long curing times.

### 3.2.3 Flexural tensile strength

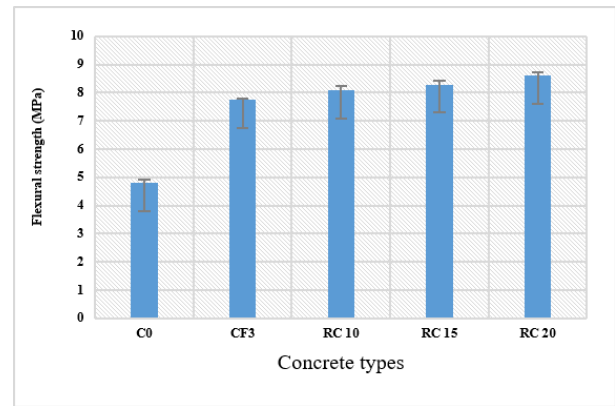
The findings result of flexural strength shown in Figure 7 represent the mean values obtained from three specimens.

From the evolution of flexural strength, it is clear that there is a similar trend to the compressive strength. The substitution of different rates of CWS leads to an increase in flexural strength. The most significant value was found with the 20% mixture of ceramic waste sand, which presents a gain of 9 and 7% compared to CF 3 concrete and a gain of 82 and 55% compared to C 0 concrete at 28 and 90 days, respectively.

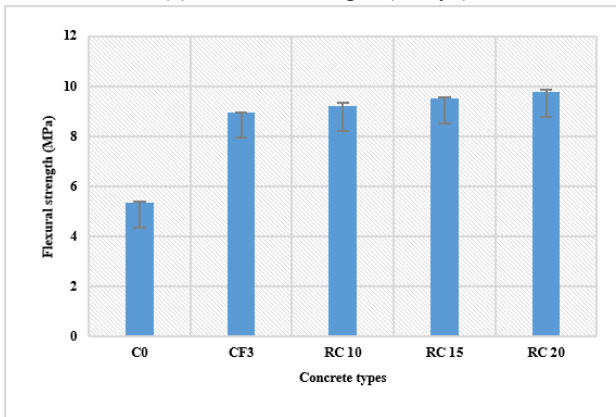
In fact, the flexural strength of concrete that contains CWS keeps getting increased for a number of reasons, one of which is the presence of fine particles that make the concrete more compact and boost its flexural strength [45]. In addition, the hardness of the grains and the rough texture of CWS, which may have enhanced the adherence of the aggregates to the cement paste, elucidated this increase in flexural strength as confirmed [46] that the microstructure inside the interfacial transition zone between recycled ceramic aggregates and paste is higher than that between natural aggregates and paste, resulting in enhanced mechanical strength.



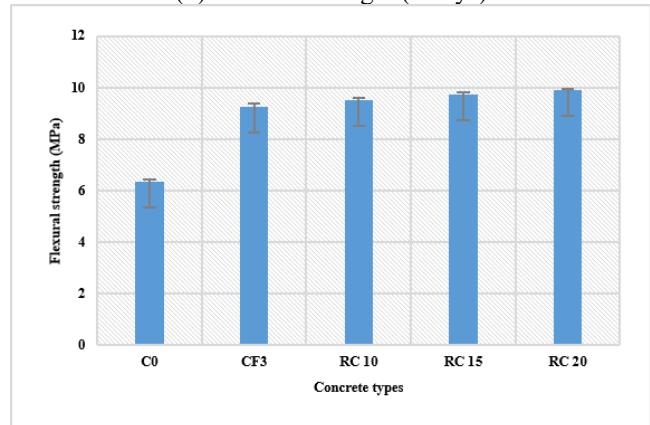
(a) Flexural strength (3 days)



(b) Flexural strength (7 days)



(c) Flexural strength (28 days)

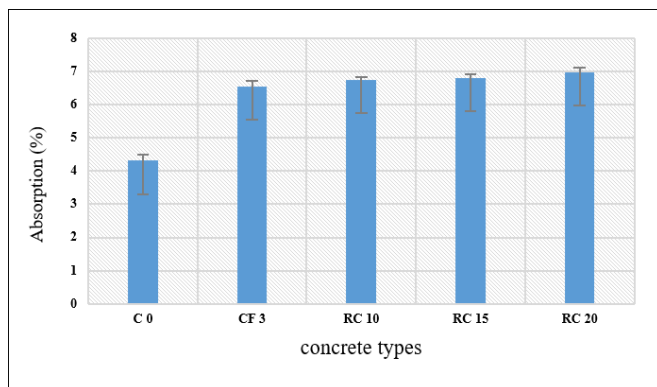


(d) Flexural strength (90 days)

**Figure 7.** Variations of compressive strength of mix concretes

### 3.2.4 Immersion absorption

Figure 8 shows the water absorption test results for all specimens.



**Figure 8.** Variation of water absorption coefficient

It is clear that the water absorption of concrete C0, CF3, RC10, RC15, and RC20 is valued at 4.31%, 6.55%, 6.75%, 6.81%, and 6.98%, respectively. The conventional mix exhibits the lowest water absorption, while the specimen containing 20% Cws exhibits the highest absorption. An increase in water absorption was observed with rising percentages of CWS. This is due to the natural properties of CWS, which is a porous particle [47] whereby it absorbs a higher amount of water as compared to natural sand. The results accord with other studies by Rao Hunchate et al. [48] and Martínez et al. [49], which show that CWS has a significant capacity for water absorption attributed to its high

coefficient rate. The standard deviation is low for all mixes, ranging from 0.09 to 0.18, and all CV% values are very low ( $\leq 4.2\%$ ), confirming excellent experimental repeatability.

### 3.2.5 Scanning electron microscopy analysis

Figure 3(c) reveals a highly heterogeneous structure, marked by the presence of angular grains, probably derived from ceramic fragments, well embedded in the cement paste. These particles have a smooth, dense surface, with visible hydration products, suggesting their chemical inertness. Surrounding these grains is a hydrated cementitious matrix, whose flaky, porous appearance indicates the presence of C-S-H (hydrated calcium silicates), contributing to the cohesion of the material [50]. Several ITZs are visible at the boundary between the ceramic grains and the paste; these interfaces, which are sometimes irregular and well structured, play a crucial role in the adhesion and durability of the concrete. Porosity is also well marked in the paste, with dispersed micrometric voids that can adversely affect permeability and resistance to aggressive agents. Taken together, these results show that the addition of ceramic waste slightly improves the compactness of the concrete, as well as its ductility and durability in the face of aggressive environments [51].

### 3.2.6 Shrinkage

The shrinkage results for different sand concretes are shown in Figure 9.

The results explicitly indicate that the drying shrinkage of all sandy concrete increases with a greater substitution of DS by ceramic waste sand. The increase in shrinkage can be attributed to the roughness and irregularity of CWS particles, which create more connected pores in the concrete. In

addition, the considerable water absorption of CWS significantly influences drying shrinkage. During mixing, the increased porosity allows for higher moisture retention within the microstructure. As the concrete dries, the gradual evaporation of this absorbed water induces higher capillary tension, resulting in increased shrinkage [52]. Numerous studies confirm these results and indicate that the shrinkage of

concrete made from recycled ceramic aggregates exceeded that of concrete made with natural aggregates [53, 54].

It is true that CWS has a positive effect on shrinkage because it contains a high proportion of fines, but the results remain within the norm, especially when combined with TWF fibres in the first place.

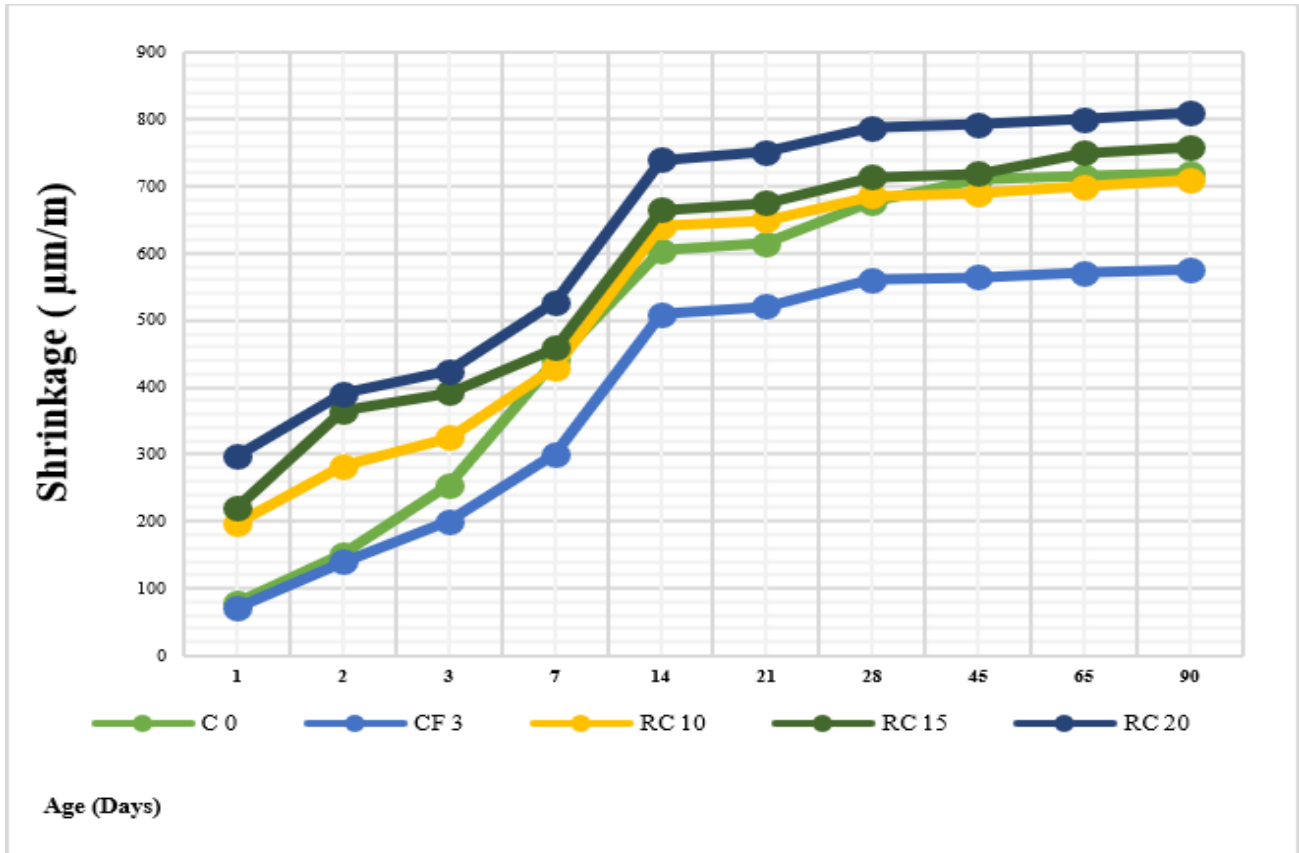


Figure 9. Shrinkage evolution of manufactured concrete

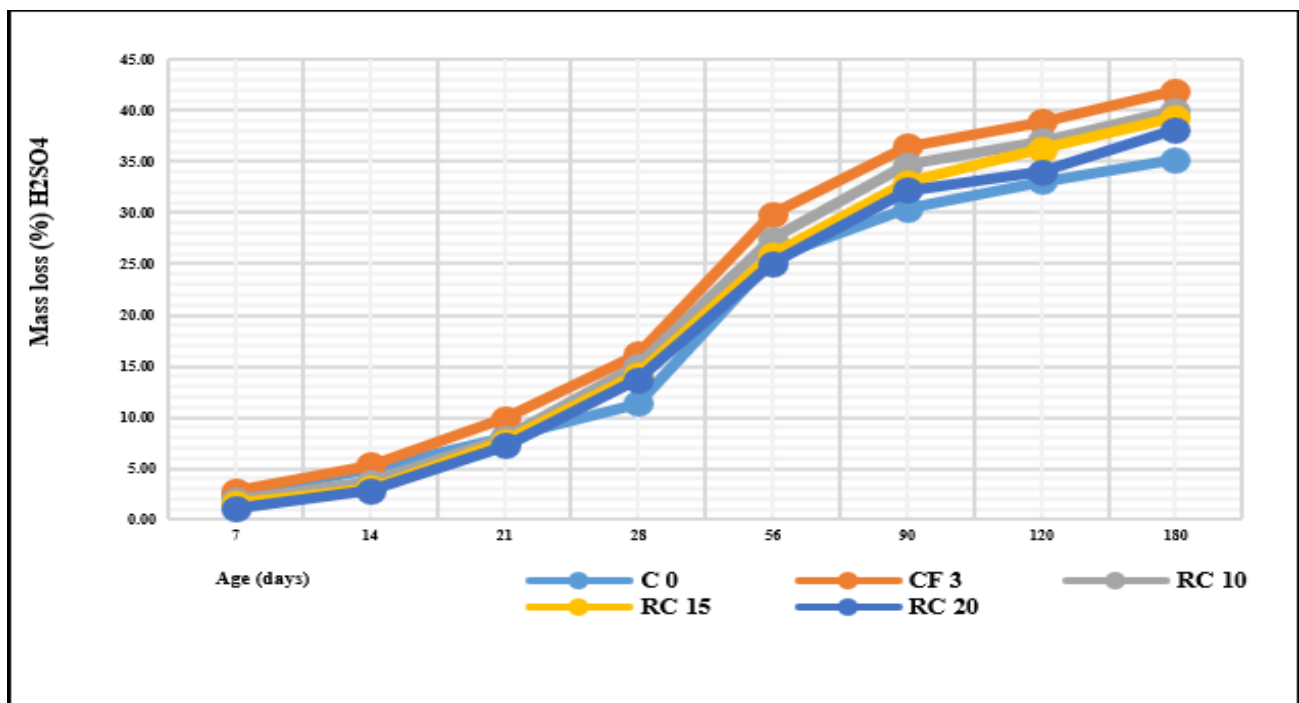
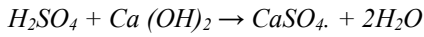


Figure 10. Mass loss of concrete as a function of immersion time in a 5% H<sub>2</sub>SO<sub>4</sub> solution

### 3.2.7 The effect of sulphuric acid

Over the course of 180 days, Figure 10 shows how the mass loss for mixed concrete changes with time spent in a 5% H<sub>2</sub>SO<sub>4</sub> solution. Sulphuric acid reacts with cement components, particularly calcium hydrates, creating by-products that can weaken and damage the concrete. This is known as a sulphuric acid attack as follows:



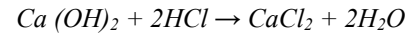
Sulphuric acid + calcium hydroxide → gypsum

From Figure 10 it is clear that all the concretes tested show a continuous loss of weight throughout the immersion period. Also, there is an inverse relationship between increasing the rate of substitution of natural sand by recycled sand and resistance to sulphuric attack. On the other hand, the concretes incorporating sand from ceramic waste show relatively similar weight losses, which are low compared with those illustrated by the control concrete (CF3). At an age of 180 days, the mass losses compared with the control concrete are of the order of less than 4, 6, and 9% for concretes RC10, RC15, and RC20, respectively. The concrete containing 20% ceramic sand performed best. The addition of ceramic sand could therefore reduce the susceptibility of concrete to attack by sulphuric acid through several mechanisms: Firstly, the pozzolanic Activity of Ceramic waste materials which, exhibit pozzolanic properties, reacting with calcium hydroxide produced during cement hydration to form additional calcium silicate hydrates. This reaction reduces the amount of calcium hydroxide available, which is susceptible to acid attack, thereby

improving the concrete's resistance to sulfuric acid [55]. Also, the microstructural Refinement of the fine particles of ceramic waste which can fill voids within the concrete matrix, leading to a denser microstructure. This densification reduces porosity and permeability, limiting the ingress of aggressive agents like sulfuric acid [56].

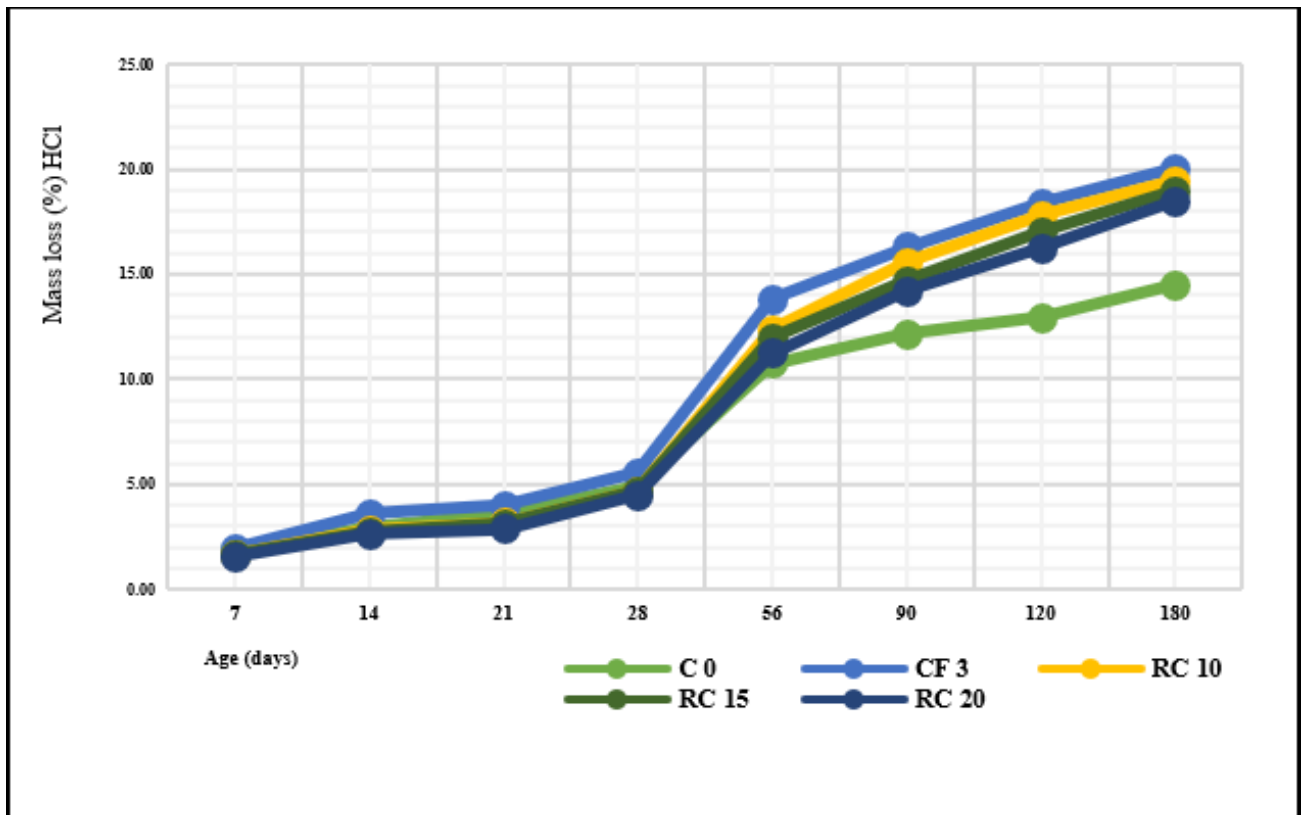
### 3.2.8 The effect of Hydrochloric acid

The results concerning the variation in mass loss of concrete specimens immersed in the HCl solution are presented in Figure 11. The rate of attack recorded depends on the solubility of the product following the reactions developed within the samples, as follows:



calcium hydroxide + hydrochloric acid → calcium chloride + water

From Figure 11 it is clearly shown that all concretes tested show a progressive weight loss over time when exposed to HCl acid. At 28 days, the impact of hydrochloric acids intensifies, leading to a significant increase in mass losses. At the end of 180 days, CF3 showed the greatest loss of mass with 20% of its weight. However, with the incorporation of CWS, the durability of fibres and concrete against HCl acid is enhanced, and with 20% of CWS, the mass loss becomes 18.5% better than CF3. This improvement is due to the incorporation of increasing rates of ceramic waste sand, which had a positive impact on the chemical resistance of the reference concrete to attack by HCl acid [57].



**Figure 11.** Mass loss of concrete as a function of immersion time in a 5% hydrochloric acid (HCl) solution

The findings for both types of attacks on concrete can be explained by a number of factors:

- The resistance of the silicates and oxides present in

ceramic sand, which are not easily attacked by aggressive agents [58].

- The fine particles of recycled sand, although

relatively reactive, generate a moderate pozzolanic effect, and the hydrates formed help to fill certain capillary interstices between the grains of sand [59].

- Recycled sand comes from ceramics that are free of metals or elements likely to interact negatively with sulphates and chlorides, which helps to limit the effects of attack [60].

A comparison of the resistance of concrete to chemical attack by sulphuric acid and hydrochloric acid shows that concrete is more vulnerable to sulphuric acid than to hydrochloric acid.

However, overall performance will depend on a number of factors, such as the exact percentage of ceramic sand used, the grain size of the sand, the quality of the cement, as well as immersion conditions, including acid concentration and exposure time [61, 62].

#### 4. CONCLUSIONS

This study highlights the potential for further development of eco-friendly reinforced sand-concrete using a wider range of recycled materials (a combination of tie wire fibers and CWS).

Based on the results obtained in this study, it can be clearly seen that:

- The tie wire fibre gives a satisfactory slump test result at a ratio of 1.2%, which provides good manipulability to the concrete for easier use.
- The density of sand concrete increases moderately with the fiber content due to the higher density of tie wire fibers.
- The tie-wire fibers have a positive effect on improving compressive and flexural strength. At a ratio of 1.2%, there was a gain in both the compressive and flexural strength of about 38% and 66% at 28 days, respectively.
- The use of tie wire fibers can produce reinforced sand concrete with satisfactory deformability and uniformity, in line with current developments in construction materials.
- The use of ceramic waste sand as a partial replacement of DS in the reinforced sand concrete contributes to reducing its workability and air content but slightly increases its density.
- The incorporation of 20% of CWS achieved an increase in strengths of 36% and 9% of compressive and flexural strength compared to the CF 3 concrete at 28 days.
- The water absorption coefficient of sand concrete increase with the incorporation of CWS. We can address this problem by wetting the ceramic waste sand before incorporating it into the sand-based concrete components.
- SEM analyses revealed that incorporating 20% of CWS improved the microstructure of the blended sand concretes. It was denser than the control C0. The excellent mechanical properties can be justified by the pozzolanic effects of this proportion, the presence of CSH gel, and the influence of ITZ between CWS and paste.
- The use of CWS in dune sand concrete enhances its acid resistance. RC 20 has superior resistance to acid attacks ( $H_2SO_4$  and HCl). Consequently, the

reinforced sand concrete with CWS enhances the performance of concrete exposed to  $H_2SO_4$  and HCl acid attacks.

According to the study results, the first idea that tie wire could be used as a fiber and CWS as an aggregate for making reinforced sand concrete elements that would work in a range of curing conditions was correct. These waste materials can solve a few problems, like the expense of commercial fibers and the lack of aggregates in construction sites, and reduce environmental pollution.

#### 4.1 Limitation and future directions

Given the challenges ahead of making reinforced recycled sand concrete more efficient and widely used, especially in durable construction, future work must focus on improving the properties of the raw materials in thoughtful ways. We further recommend establishing a set of guidelines so that TWF and CWS can become more conventional options for recycled fibre-sand concrete. Furthermore, we recommend conducting more experiments on shrinkage and capillarity to further explore the behaviour of recycled reinforced sand concrete's durability. We must also conduct further long-term studies to examine the durability and longevity of these types of concrete.

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## NOMENCLATURE

DS	Dune sand
CWS	Ceramic waste sand
LS	Limestone filler
SP	Superplasticizer
W	Water
C	Cement
TWF	Tie wire fibers
CV	Coefficient of variation