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Effect of Recycled Fibers on the Mechanical Properties and Durability of Sand Concrete

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Recycling waste in construction materials is part of a sustainable development approach aimed at creating new materials with characteristics that have been shown to be competitive with traditional materials. In this context, this study aims to recover steel, copper and aluminum wastes from blacksmiths' workshops together with the reuse thereof in the form of reinforcing fibers in sand concrete. However, in order to assess the impact of this waste on the concrete properties, we introduced such wastes in the form of fibers at different proportions (0.4 %, 0.8 % and 1.2 %). Further, a series of tests was then carried out to determine the evolution of the concrete characteristics in the fresh state (workability and density) and in the hardened state (compressive strength, flexural strength, compressive strength obtained using a sclerometer and the speed of ultrasonic waves), as well as the concrete's durability (absorption coefficient by immersion, by capillarity and the porosity accessible to water). In closing, the behavior of the concrete was assessed in the face of a chemical attack by H_2SO_4 and HCl by measuring mass loss. In virtue of thus, the results obtained demonstrated a positive evolution of certain properties of sand concrete as a function of the type and percentage of fibers incorporated into the composition of the concrete.

Keywords: sand concrete, recycled fibers, formulation, mechanical properties, durability.

1. INTRODUCTION

Sand concrete has become one of the construction materials competing with traditional concrete because of its mechanical, physical and thermal properties together with its durability, as well. Besides, it has been used in various construction projects, in respect such as underground works, dams, pavements, airports and road works [1 – 3]. In addition, it is alike used in injection works, the rehabilitation of old buildings and can be used as an alternative to shotcrete [4]. Nonetheless, this type of concrete still has certain limitations that are attracting the interest of researchers, in particular problems relating to thermal and acoustic properties, as well as the problem of shrinkage, which represents one of the main obstacles for sand concrete, as it has shown to be higher than that observed one in traditional concrete [3]. Additionally, the tensile strength of sand concrete is often low, resulting in reduced resistance to cracking. On the other hand, quite a few studies have been carried out to find alternative economic, ecological and technological solutions to develop and improving the performance of sand concrete.

The process of introducing fibers into the composition of concrete represents a new method and an effective solution for reducing the problems that can appear in sand concrete, as this depends greatly on the geometry and type of these fibers; in respect such as glass, vegetable, rubber, metallic (ferrous and non-ferrous), aramid and other industrial fibers. Its distribution within the concrete is random, precise and discontinuous, with specific lengths and geometries [5]. According to Hannant *et al.* (1978), fiber-reinforced concrete or mortar has better flexural tensile strength than ordinary concrete, while reducing shrinkage and the resulting cracks [6].

In 2020, Ammari *et al.* (2020) carried out a study on the development of a new lightweight sand concrete based on hybrid fibers: barley straw and steel fibers. However, the aim was to improve mechanical properties by incorporating different proportions of steel fibers (0 %, 0.5 %, 1 %, 1.5 % and 2 %) by volume. The reinforcement process improved the physical and mechanical properties of the concrete, in particular compressive strength, with a slight increase in thermal conductivity and density, as well as a significant reduction in shrinkage and thermal diffusion [7]. In this respect, the effect of polypropylene fibers and metal fibers on the properties of sand concrete was investigated by Melais *et al.* (2015). Thus, the results demonstrated an increase in compressive and tensile strength, along with an improvement in concrete cohesion and density [8]. More and more, another study conducted by Ben Othman *et al.* (2017) concluded that polypropylene fiber-reinforced sand concrete slightly reduces mechanical properties, but significantly improves shrinkage behavior. An optimum value of 1 % of these fibers was identified for such type of reinforced concrete, intended for the construction of

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pavements for low-traffic roads [9]. Similarly, Elrefaei *et al.* (2023) conducted a study on the effect of using metal fibers to reinforce sand concrete slabs; the results demonstrated an improvement in tensile strength, hardness and toughness after cracking at an optimum fiber value of 30 kg/m^3 [10]. Nevertheless, another study conducted by Ammari *et al.* 2020 evaluated the effects of steel lignocellulose hybrid fibers on the durability of sand concrete. As a consequence, the results demonstrated that the depth of carbonation decreased as the proportion of steel fibers increased. In addition, steel fibers help to reduce the porosity of the concrete, resulting in a reduction in capillary absorption and porosity accessible to water [11].

Likewise, fibers have a limited positive effect on compressive strength after freeze-thaw and wet-dry cycles, and on resistance to aggressive environments, as well. In the same context, plant fibers have been used in sand concrete to improve its thermal, physical and mechanical performance by Bederina *et al.* (2007), Belhadj *et al.* (2014) and Bederina *et al.* (2009). In light of this, they found that the use of fibers gave better results in terms of shrinkage, thermal diffusion, toughness and ductility. In the same context, recycling solid waste stands for an environmentally sustainable approach and an important source of raw materials for various fibers that can be used in concrete [12 – 14]. On the one hand, recovery helps to reduce the impact of this waste on the environment and human health, whilst at the same time reducing the consumption of natural resources and energy [15].

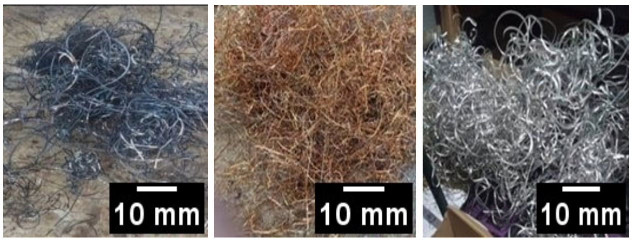
Amongst the most common solid wastes are metal wastes from the manufacture of steel, stainless steel, cast iron and various metal parts, as well as aluminum, copper and nickel. Further, this waste comes in the form of lumps, granules and shavings. Algeria's metal products industry is booming, with production set to reach 05 million tons of iron and steel by 2022. This corresponds to the production of more than 1.2 million tons of various types of waste per year, with a recovery rate of around one-third, or around 360.000 tons of waste [16]. Nevertheless, this poses major problems in reducing their impact on the environment, particularly given the lack of appropriate storage depots for this type of waste.

Several studies have been carried out into the recovery and recycling of ferrous and non-ferrous scrap metal in concrete and mortar, in the form of reinforcing fibers. These fibers improve mechanical strength and resistance to fatigue, impact, shattering and corrosion, while reducing crack propagation in concrete. Therefore, these improvements are achieved when the percentage of reinforcement is specified at between 01 and 02 % by volume [17]. Copper waste is part of non-ferrous metal waste, mainly from production plants as well as electrical rehabilitation work on buildings, water and heating pipes. Nevertheless, due to the anti-corrosive nature and smooth surface of copper fibers, Ndruru *et al.* (2021), conducted research into the use of waste copper fibers from electronic cables in concrete used for pavements. Then, they introduced varying proportions of 0 %, 0.5 %, 01 % and 1.5 % fibers. As a consequence, the results demonstrated an increase in the compressive and tensile strength of the concrete as a function of the percentage of copper waste fibers [18]. However, to address the problem of cracks in concrete, Malli Kharjuna and Srinivasa (2017) conducted a study in 2017 on the possible use of copper wires as fibers. In this regard, they used proportions of 0 %, 0.5 %, 01 %, 1.5 % and 02 % of the cement weight. As a consequence, the results were encouraging, as the strength of the concrete increased and cracks were reduced [19]. Nadhom *et al.* (2023), tested the effect of using copper fibers (from damaged electrical wires) of different diameters on pure gypsum. Thus, they recorded an increase in compressive strength when copper fibers were added to the mix, depending on the diameter thereof [20].

More to the point, aluminum stands for another type of non-ferrous metal waste, which is characterized by its low density, lightweight and high resistance to corrosion compared with steel. Further, aluminum scrap is estimated to total around 17 million tons worldwide, originating in the automotive, construction and metalworking industries in blacksmith's shops. On the other hand, because of its ease of recycling, Sabapathy *et al.* (2019), used aluminum electrical wires as reinforcement fibers for concrete and studied their effect on mechanical properties at rates ranging from 0 % to 2 %. After 28 days, the test results demonstrated a relative improvement in compressive and tensile strength depending on the proportions and shape of the fibers used [21]. In a similar context, Rajaraman (2017), used aluminum fibers in concrete replacing different proportions of cement and analyzed their effect on mechanical properties. In virtue of this, the results revealed a significant increase in compressive and tensile strength compared to the reference concrete [22]. Additionally, Mediyanto *et al.* (2018), investigated the impact of introducing aluminum fibers on the compressive strength of lightweight concrete after exposure to high temperature. Subsequently, the results demonstrated an improvement in strength, with a minimum recovery time in compressive strength at 28 days for lightweight concrete made from aluminum fibers, compared to the reference concrete [23].

On the other hand, steel accounts for the vast majority of ferrous waste, due to its widespread use in various fields. Likewise, it is well known that this type of waste is not biodegradable, but it is recyclable and can be used in the form of fibers in concrete or mortar, particularly as it is characterized by its high compressive and tensile strength. However, this was demonstrated in the study conducted by Kishore (2019), where the use of steel fibers in concrete resulted in an increase in compressive and tensile strength, with a fiber content of 0.5 % [24]. Nevertheless, in the study by Mello *et al.* (2014), steel fibers were added to concrete along with other fibers to determine their impact on the properties of the composite. As a consequence, the results demonstrated a significant increase in the compressive and tensile strength of the concrete compared to other mixes [25]. Above and beyond, Sarabi *et al.* (2017), carried out a study on reducing the heat of hydration generated by water, which can cause thermal stresses leading to cracking in high density concrete, using turned steel waste fibers while reducing the amount of cement. Subsequent to which, the results demonstrated a reduction in heat of hydration stresses, and an increase in compressive and tensile strength with 0.5 % fiber content, as well [26].

Based on the aforementioned studies, we have carried out this study, the aim of which is to investigate the possibility of reusing industrial waste from blacksmiths' workshops, in particular, waste from the sawing of steel, copper and aluminum parts by machines (as shown in Fig. 1). Besides, this waste is used as fiber reinforced sand concrete with rates of 0.4 %, 0.8 % and 1.2 % and to study its impact on properties in the fresh and hardened states and its durability.



a b c

Fig. 1. Blacksmith's waste: a – steel; b – copper; c – aluminum

2. USED MATERIALS

The cement used is a CPJ-CEMII/A S-L 42.5, from the cement plant Hdjar Essoud in Skikda (eastern part of Algeria), with an absolute density of 3.08 g/cm³ and a specific surface area assessed to 3669 cm²/g.

The used sand is siliceous dune sand (SD) class 0/1, of a rolled nature originating from Oued Zhor – Skikda. This sand is clean with an absolute density of the order of 2.640 g/cm^3, and its particle size curve is demonstrated in Fig. 2.

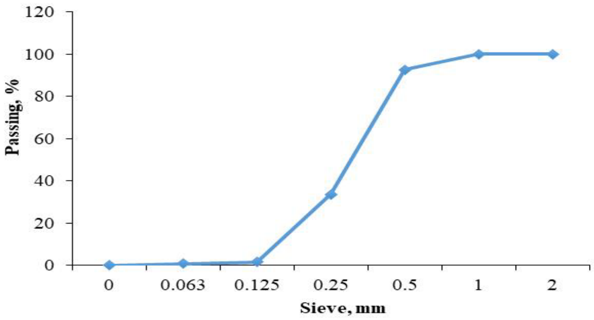
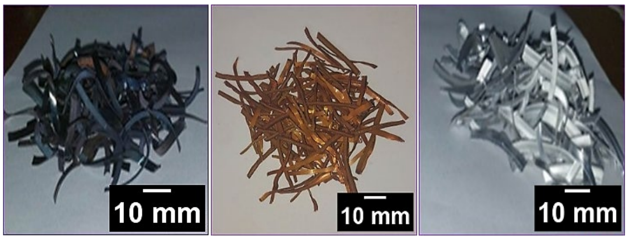


Fig. 2. Granulometric curve of sand

The fines (F) used in this study are limestone fines from the quarry of Ben Azouz located in the eastern part of Algeria, 95 % of which is calcium carbonate, more than 70 % of which passes through a 0.08 mm sieve, and characterized by an absolute density of 2.741 g/cm^3.

The used superplasticizer (SP) is Master Glenium 26, a high water reducer for low W/C ratio concrete, in the form of a brown liquid with a density of 1.08g/cm^3.

The used fibers were obtained from the sawing of various metal parts in forge workshops. They are made up of two types of recycled fibers: fibers from ferrous metal waste, represented by steel fibers (SF), and fibers from non-ferrous metal waste, represented by copper fibers (CF) and aluminum fibers (AF). The waste was recovered, sorted and cut into specific lengths of between 02 and 03 cm (as shown in Fig. 3). The fibers have different properties, as demonstrated in Table 1.



a b c

Fig. 3. Recycled fibers: a – SF; b – CF; c – AF

Table 1. Properties of recycled fibres

Properties	Steel fibers (SF)	Cooper fibers (CF)	Aluminum fibers (AF)
Density, g/cm^3	7.98	9.27	2.49
Stress, MPa	268.21	419.8	50.34
Elongation, mm	3.74	17.75	8.48
Strain	0.748	0.355	0.1696
Young's modulus, MPa	358.57	1182.54	5.94
Fe, %	93	–	–
Cu, %	–	≥ 99.90	–
Al, %	–	–	≥ 92

According to the characteristics demonstrated in Table 1, we can notice that:

1. Copper and steel fibers have the highest densities, the fact of which means that they are heavier and denser, whilst aluminum fibers have the lowest density. Aluminum fibers make concrete lighter [27].
2. Copper and steel fibers have higher stress values, with values of 419.8 MPa and 268.21 MPa respectively, compared with aluminum fibers; the fact of which means that copper and steel can withstand higher loads before deformation or failure.
3. Copper fiber has a higher elongation value, indicating that it has a greater capacity to deform before breaking. Thus, the higher the elongation, the higher the ductility [28].
4. Copper and steel fibers have a high Young's modulus, the fact of which means that they have a higher stiffness than aluminum fibers.

3. EXPERIMENTAL PROGRAMME

The aim of this work is to reuse blacksmithing waste (steel, copper and aluminum) as fibers in the composition of sand concrete. Besides, the reference sand concrete (SC0) without fibers was formulated using the Sablocrete method [3], with the fixed parameters being the W/C ratio = 0.68, the fine content and the admixture content. The selected formulations were obtained by introducing fibers into the reference formulation at rates of 0.4 %, 0.8 % and 1.2 % whilst maintaining the same volume. Nine formulations were obtained (as shown in Table 2). The tests carried out on the different formulations are:

1. density: the density of the mixes in the wet state was measured in accordance with standard NF EN 12350-6;

Table 2. Composition of mixtures

Type of concrete	CEM II, g	DS, g	F, g	SP, g	W, L	SF, g	CF, g	AF,g
SC0 %*	8934.82	25339.78	5628.94	82.71	6075.68	0	0	0
SCS0.4 %*	8934.82	25116.47	5628.94	82.71	6075.68	675.00	0	0
SCS0.8 %	8934.82	24893.16	5628.94	82.71	6075.68	1350.00	0	0
SCS1.2 %	8934.82	24669.85	5628.94	82.71	6075.68	2025.00	0	0
SCA0.4 %*	8934.82	25116.47	5628.94	82.71	6075.68	0	0	210.62
SCA0.8 %	8934.82	24893.16	5628.94	82.71	6075.68	0	0	421.24
SCA1.2 %	8934.82	24669.85	5628.94	82.71	6075.68	0	0	631.86
SCC0.4 %*	8934.82	25116.47	5628.94	82.71	6075.68	0	784.12	0
SCC0.8 %	8934.82	24893.16	5628.94	82.71	6075.68	0	1568.24	0
SCC1.2 %	8934.82	24669.85	5628.94	82.71	6075.68	0	2352 .35	0

*SCS: Sand concrete reinforced by steel fibers
*SCA: Sand concrete reinforced by aluminum fibers
*SCC: Sand concrete reinforced by copper fibers

2. workability: the slump of fresh concrete was measured using an Abrams cone in accordance with standard NF P 18-451;
3. compressive strength: the compressive strength test is carried out on half-prisms measuring 7 × 7 × 7 cm^3 at 7, 28 and 90 days in accordance with standard NF EN 12390-3;
4. flexural tensile strength: the flexural tensile test was carried out on prismatic specimens measuring 7 × 7 × 28 cm^3 at 7, 28 and 90 days in accordance with standard NF EN 12390-5;
5. sclerometer test: the test was carried out using a sclerometer on samples measuring 15 × 15 × 15 cm^3 after 28 days of curing in water, in accordance with standard NF EN 12504-2;
6. ultrasonic velocity: the ultrasonic velocity was obtained on cubic samples measuring 15 × 15 ×15 cm^3 after 28 days in water, in accordance with standard NF EN 12504-4;
7. dynamic modulus of elasticity: the dynamic modulus of elasticity of the samples studied was calculated using the equation of Neville (2011) [29], in accordance with standard NF EN 14146;
8. water absorption by immersion: the coefficient of absorption by immersion is measured on samples measuring 4 × 4 × 16 cm^3 in accordance with standard NBN B 15-215;
9. water-accessible porosity: the water-accessible porosity is measured in accordance with standard NF P18-459 on samples measuring 4 × 4 × 16 cm^3;
10. water absorption by capillarity: the coefficient of absorption by capillarity is measured on samples measuring 4 × 4 × 16 cm^3 in accordance with standard NF EN 772-11;
11. chemical attack: chemical attack was assessed by mass loss on samples measuring 5 ×5 ×5 cm^3 after their initial cure in water for 28 days, followed by exposure to chemical media 5 %H_2SO_4 and 5 %HCL, in accordance with ASTM standard C-267-96.

4. RESULTS AND DISCUSSION

4.1. Density

In light of the results demonstrated in Fig. 4, it can be noticed that the concrete density increases with the increase in the incorporation rate of steel and copper waste fibers. Thus, reaching a maximum value of 2.282 g/cm^3 and 2.25 g/cm^3 respectively at a rate of 1.2% in comparison with the reference concrete and based on aluminum fibers. Besides, this increase in density can be explained by the high density of steel and copper waste fibers, which is three times higher than the one of concrete without metal fibers [30]. Conversely, the density decreased with increasing percentage of aluminium fibres in the mix, where the minimum density value was recorded at 2.129 g/cm^3 at 1.2 %. Therefore, this is due to the advantage of aluminium in reducing the density of composites [31].

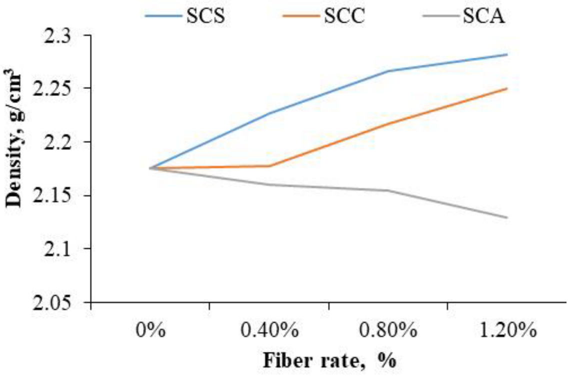


Fig. 4. Variation in density as a function of fiber content and type

4.2. Workability

Consequently, the results demonstrated in Fig. 5 show that the incorporation of recycled steel and aluminum fibers in sand concrete leads to a reduction in its workability, whatever the proportion of fibers. As a fact of matter, the slump went from 26 cm in the reference concrete to 24.3 cm and 24 cm respectively for the SCS and SCA mixes with a fiber content of 1.2 %. However, this decrease can be attributed to the intertwining of fibers with each other in the concrete mix and their non-uniform distribution, which creates stiffness and workability difficulty properties [10–32].

For the SCC mix, the workability behaviour was the opposite compared to the other mixes, as we observed an increase in workability, which reached a maximum value of 27 cm with an optimum fiber content of 0.4 %. Nonetheless, beyond this value, the workability of the concrete decreases reaching 25 cm with a fiber content of 1.2 %.

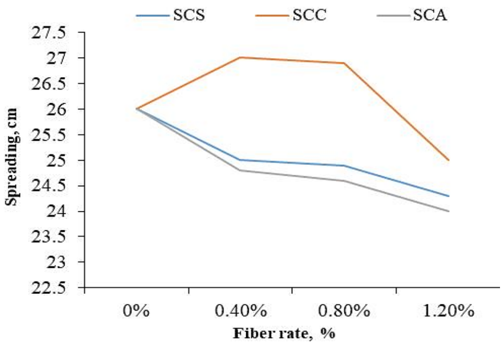


Fig. 5. Variation in workability as a function of fiber content and type

As the proportion of fibers increases, the workability decreases due to the effect of the fibers on the amount of paste flow, whereas the increase in fibers from 0.4 % to 1.2 % decreases the amount of slump current [33].

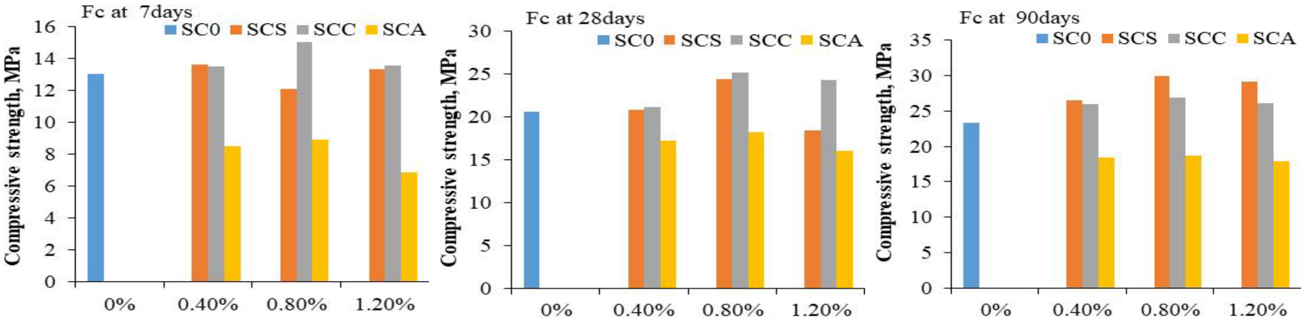
4.3. Compressive strength

The introduction of recycled steel fibers into the sand concrete (as shown in Fig. 6) resulted in a slight increase in compressive strength at 7 days, with values of 0.4 % and 1.2 % of the fibers. Nonetheless, a decrease in strength was observed at a rate of 0.8 %. Similarly, the results at 28 days were similar to those in the short term, showing an increase in strength with increasing fiber content up to 0.8 %. Above this value, the compressive strength decreased compared with the reference concrete. At 90 days, a considerable increase in strength can be observed, whatever the fiber content, with a maximum value of 29.9 MPa at 0.8 % fiber content. Above and beyond, this increase in strength is attributed to the role of the steel fibers as reinforcing elements in the cementitious matrix, preventing the appearance of cracks and deformations under load. Further, the decrease in compressive strength observed at certain levels of steel fibers may be due to their shape, orientation and distribution within the samples [10 – 34 – 35].

In the case of the SCC mix, the results demonstrated in Fig. 6 b show that the incorporation of copper waste fibers led to an increase in compressive strength, regardless of their proportion in the mix, at 7.28 and 90 days, with an optimum value of 0.8 % to obtain the highest strength. Further, this improvement can be attributed to the random distribution of fibers within the concrete mix [36].

More to the point, the results indicate that the compressive strength of concrete containing proportions of 0.4 %, 0.8 % and 1.2 % of aluminum waste fibers (as shown in Fig. 6 c) decreased at all ages. As the proportion of fibers increased, the strength decreased. However, this decrease can be attributed to the low density of the aluminum concrete due to the low density of the aluminum fibers [37].

Furthermore, the decrease in compressive strength could be attributed to the possibility of a reaction between the aluminum waste fibers and the $Ca(OH)_2$ formed by the hydration of the Portland cement, resulting in the release of hydrogen gas. Moreover, this can lead to the formation of voids and a porous structure in the concrete [38], which become visible on the surface of the samples (as shown in Fig. 7).



a b c

Fig. 6. Variation in compressive strength (*Fc*) as a function of recycled fiber content and type: a – 7 days; b – 28 days; c – 90 days

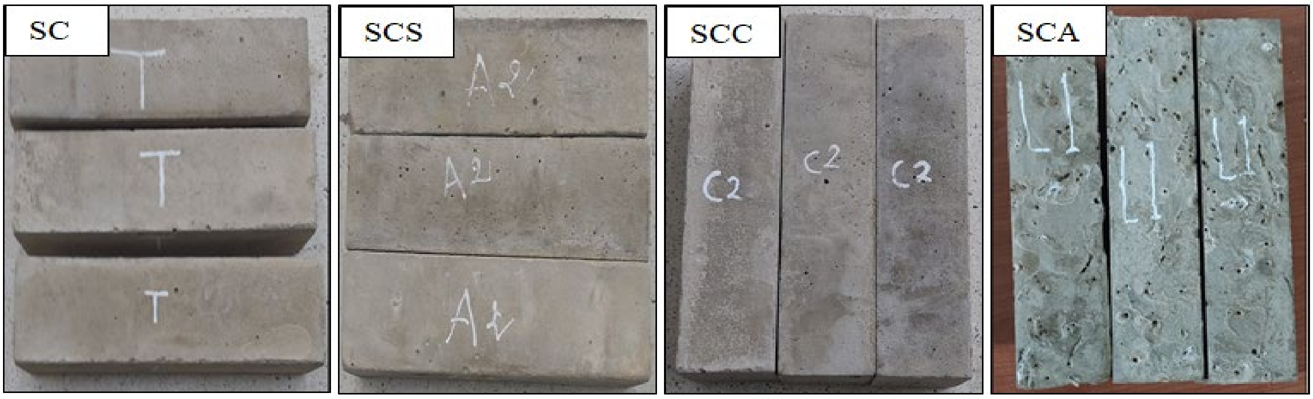


Fig. 7. Condition of the specimens after form removal: sand concrete (SC), sand concrete reinforced by steel fibers (SCS), sand concrete reinforced by copper fibers (SCC), sand concrete reinforced by aluminum fibers (SCA)

Comparing the different formulations studied, it can be noticed that the steel and copper fibers had a positive effect on the compressive strength of the concrete compared with the other formulations. Besides, the mechanical behavior of the concrete has improved with the percentage of incorporation of these fibers. On the other hand, aluminum fibers had a significant negative impact on strength at all percentages and all ages.

4.4. Flexural strength

The results demonstrated in Fig. 8 show a significant increase in the flexural tensile strength of the concrete with an increasing percentage of steel fibers compared to the reference concrete, in the short, medium and long term. Further, it can be said that the maximum percentage of 1.2 % steel fibers (as shown in Fig. 8 a) gave the highest strength values at all ages. However, this is due to the contribution of steel fibers to improving the slip resistance of pre-existing microcracks [34].

For the SCC mix (as shown in Fig. 8 b), the addition of copper fibers at proportions of 0.4 % and 0.8 % resulted in a decrease in tensile strength of 25.07 % and 1.90 % respectively at 07 days. In this respect, this can be attributed to the cracks that form due to internal friction between the cement paste components and the copper fibers at this age [39]. Moreover, the strength continued to increase as the percentage of copper fibers increased at 28 and 90 days, thus reaching maximum values at a rate of 1.2 %, recording an increase of 47.70 % and 45.40 % respectively. Nonetheless, this is due to the strengthening of the bond between the fibers and the cementitious matrix, thus increasing the flexural strength [40]. On the other hand, it should be noted that copper fibers are characterized by a high Young's stress and modulus compared to other fibers. Hence, this provides high fracture toughness, which enhances the flexural tensile strength of concrete, even at the onset of initial cracking, due to the continuous bridging effect induced by the fibers [41].

Unquestionably, the tensile strength behavior of the SCA mix (as shown in Fig. 8 c) at 7 days is similar to the compressive strength, whereas a strong decrease in strength is observed for all proportions of aluminum fibers, which can be attributed to the smooth surface of the fibers that reduces the adhesion between the fibers and the matrix at this early age [42]. Nonetheless, the performance of SCA improves with increasing percentage of aluminum fibers at 28 and 90 days, more than ever at the maximum value of 1.2 %. However, this is due to the fact that an increase in the fiber content helps to enhance the confinement property of the fibrous concrete matrix, thus reducing the unavoidable transverse deformations [21].

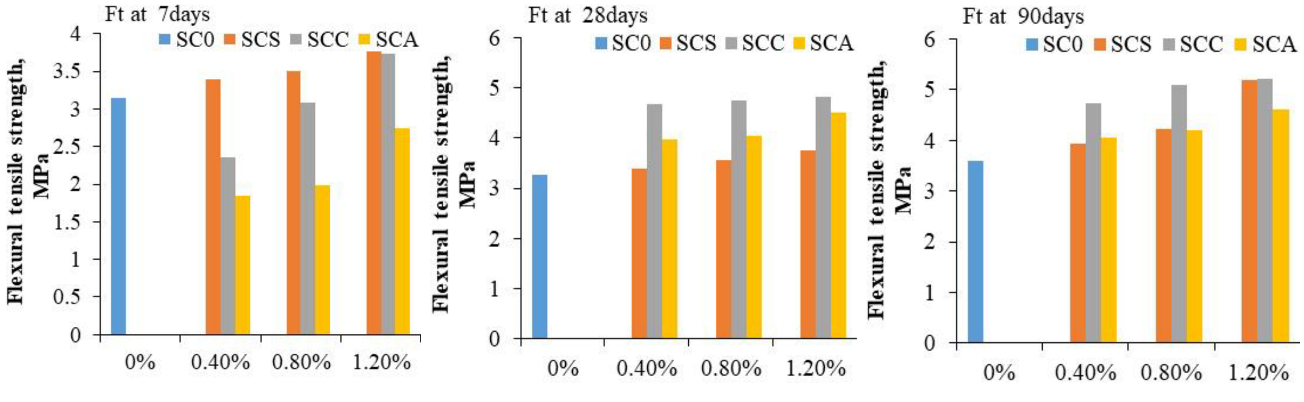
The results highlight the positive effect of the recycled steel fibers on the tensile strength compared with the other fibers and the reference concrete, at all ages. On the other hand, the SCC mix gave the highest tensile strength values in the medium and long term. In addition, after 14 days, the strength increased progressively as the percentage of aluminum fibers increased.

4.5. Compressive strength obtained by sclerometer

According to Fig. 9, the introduction of steel fibers into the sand concrete leads to a decrease in surface strength measured by the use of the sclerometer at 28 days, regardless of the proportions of these fibers, compared to the reference concrete which was more homogeneous, due to the high silica content of the dune sand, which improves the strength of concrete SC0 % at this age [15]. However, the decrease in strength can be attributed to the shape, orientation and distribution of the steel fibers within the samples [10 – 35], which negatively affect the homogeneity of the concrete.

The results for the SCC mix demonstrated a slight increase in strength at 0.8 % and 1.2 % copper fibers compared to the reference concrete, reaching a maximum value of 28.5 and 28.9 MPa respectively. However, this can be attributed to the improved homogeneity, integrity and quality of the hardened concrete [43], due to the good dispersion of copper fibers within the concrete.

Furthermore, the results obtained by the sclerometer test for the SCA mix show similar behavior to the previous results of the compressive strength at 28 days. In fact, as the proportion of aluminum fibers increases from 0.4 % to 1.2 %, the strength decreases, which may be due to the decrease in density of the SCA [37]. In addition, the formation of voids on the surface of the sample, which could result from a reaction between the aluminum waste fibers and $Ca(OH)_2$ [38], could have weakened the surface strength.



a b c

Fig. 8. Variation in flexural tensile strength (*Ft*) as a function of recycled fiber content and type: a – 7 days; b – 28 days; c – 90 days

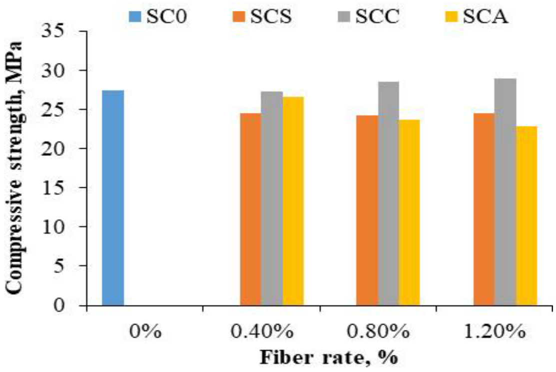


Fig. 9. Compressive strength measured by sclerometer

Undeniably, the results suggest that copper waste fibers have a positive effect on the homogeneity, integrity and quality of hardened sand concrete at 28 days, compared to steel, aluminum waste fibers and reference concrete as well.

4.6. Ultrasonic velocity

The ultrasonic test results demonstrate the positive effect of the steel fibers on the internal structure of the hardened sand concrete at 28 days (as shown in Fig. 10), in particular at a proportion of 1.2 %. Above and beyond, the ultrasonic wave velocity increased from 4.05 km/s in the reference concrete to 4.24 km/s with similar velocities recorded at the 0.4 % and 0.8 % steel fiber proportions. However, this is attributed to the reinforcement of steel fibers in the internal structure of the hardened concrete by increasing its density [43].

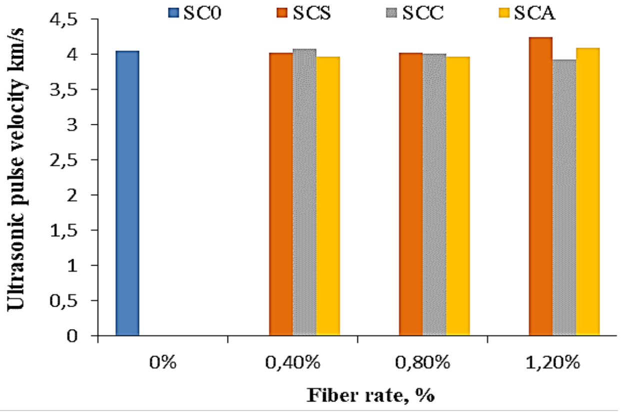


Fig. 10. Compressive strength measured by ultrasonic velocity.

The introduction of 0.4 % recycled copper fibers into the sand concrete leads to a slight increase in the pulse velocity of the ultrasonic waves, reaching 4.08 km/s, which can be attributed to the reinforcement of the homogeneity of the internal structure of the concrete. Nevertheless, a decrease in velocity is then observed with the increase in recycled copper fibers, which may be due to the way in which the fibers are distributed and partitioned in the cementitious matrix of the concrete [34].

For the SCA mix, the ultrasonic wave velocity results were lower than those for concrete SC0 %, particularly at the 0.4 % and 0.8 % aluminum fiber rates, but became closer to those of the reference concrete at 1.2 %. However, this may be due to the decrease in composition density that has previously been recorded [37].

As a fact of the matter, the results demonstrated relatively close ultrasonic wave velocity values for all formulations, with a slight increase in the SCS mix with 1.2 % waste steel fibers at 28 days.

4.7. Compressive strength obtained by use of the sclerometer/ultrasonic combination

The results obtained by use of the sclerometer/ultrasound combination (as shown in Fig. 11) demonstrate that the SCC mix with 1.2 % copper fibers has a maximum compressive strength of 19.33 MPa. However, this is explained by the improved homogeneity, integrity and quality of the hardened sand concrete, which gives it a denser and more interlocking microstructure [43]. On the other hand, it is noticed that recycled steel fibers decreased the compressive strength obtained from the sclerometer/ultrasound combination in all proportions, which is the same behavior for aluminum fibers.

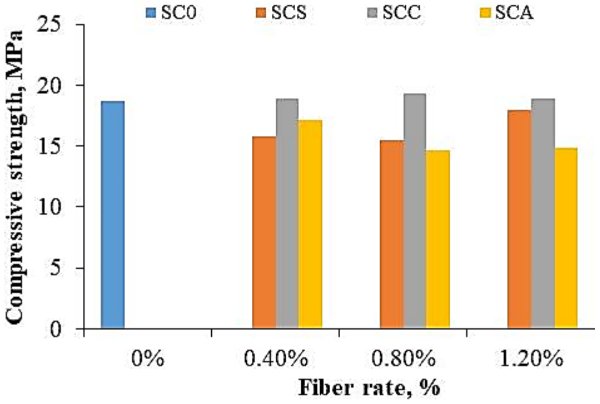


Fig. 11. Variation in compressive strength obtained by use of the combined method as a function of recycled fiber content and type

4.8. Dynamic modulus of elasticity

Comparing the reference concrete mixes and the SCS mix (as shown in Fig. 12), an increase in the modulus of elasticity of the concrete is noticed with increasing steel fiber content, which reaches a maximum value of 36.44 GPa for a steel fiber content of 1.2 %. Nevertheless, this increase can be attributed to the hardness of the steel fibers, which leads to a higher modulus of elasticity in the concrete compared to the reference concrete [44]. In virtue of this, this increase can be attributed to the hardness of the steel fibers, which leads to a higher modulus of elasticity in the concrete compared to the reference concrete [44].

As far as the SCC mix is concerned, we notice a variation in the results, where we recorded the maximum value of the modulus of elasticity with a rate of 0.8 % of copper waste fibers, whilst it slightly decreased for concretes with rates of 0.4 % and 1.2 %. However, this could be due to the negative effect of air trapped around the fibers, which affects the modulus of elasticity [45], due to frictions between the fibers and other components of the cement paste.

Categorically, the introduction of recycled aluminum fibers at proportions of 0.4 % and 0.8 % results in a slight decrease in modulus of elasticity compared with the SC0 % concrete mix. Hence, this reduction can be explained by the low modulus of elasticity of aluminum. On the other hand, concrete based on a 1.2 % rate resulted in a significant improvement in modulus of elasticity, which reached a maximum value of 32.42 GPa. However, this may be due to the fact that the high proportion of fibers helps to enhance the interlocking and bonding strength, the fact of which provides a higher modulus of elasticity for the concrete [46].

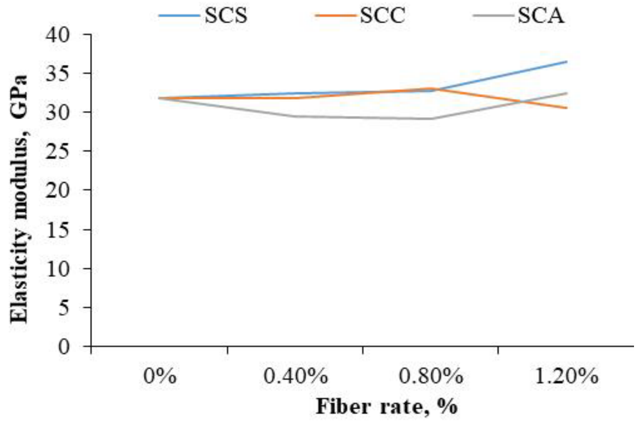


Fig. 12. Variation in modulus of elasticity as a function of recycled fiber content and type

Generally speaking, the results obtained indicate that the high proportions of recycled steel and aluminum fibers (1.2 %) improve the modulus of elasticity of sand concrete, unlike the waste copper fibers.

4.9. Water absorption by immersion

Emphatically, the immersion absorption coefficient is considered to be an indicator of the durability of concrete. Hence, the results illustrated in Fig. 13 demonstrate a reduction in the coefficient of absorption by immersion as a function of the proportions and type of recycled fibers, as they indicate that the introduction of copper waste fibers contributes to a considerable reduction in the quantity of water absorbed by immersion compared with other mixes, particularly at 0.8 % and 1.2 %. in virtue of which, this brings us to our findings on the sclerometer/ultrasound tests, which demonstrated an improvement in the homogeneity, integrity and quality of hardened concrete that led to more favourable pozzolanic effects on the physical and chemical properties of porous structures [43].

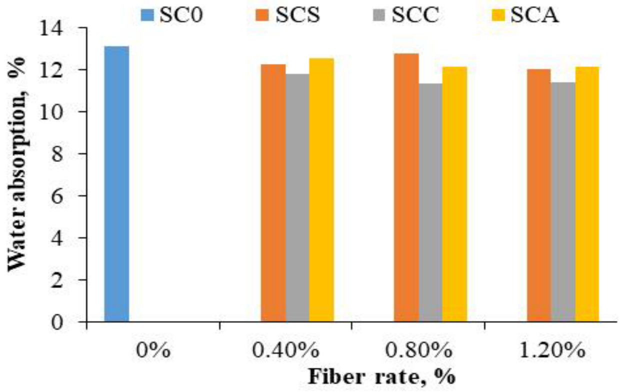


Fig. 13. Variation in water absorption by immersion as a function of the rate and type of recycled fibre

With regards to the SCS and SCA mixes, we noticed similar behavior for all proportions. Notwithstanding a slight increase in the proportion of steel fibers to 0.8 % compared with the other fibers, the absorption coefficient remains lower than that of the reference concrete. Therefore, this can be attributed to the reinforcement of the internal structure of the hardened concrete, which helps to reduce water absorption by immersion. As a consequence, the results of this study differ from the one conducted by Norambuena-Contreras *et al*. 2018, whereas a significant increase in porous structures was observed when using fibers in concrete [42]. Subsequently, this difference can be attributed to the way the fibers are positioned, oriented and distributed in the cementitious matrix.

4.10. Water-accessible porosity

The results of the water-accessible porosity (as shown in Fig. 14) test demonstrated that increasing the steel waste fiber content reduces the porosity of the hardened concrete, with a decrease of 5.94 % recorded at the maximum steel fiber content of 1.2 %. However, this can be attributed to the recorded high density of the mix resulting from the improved porous microscopic structure of the solid concrete [43].

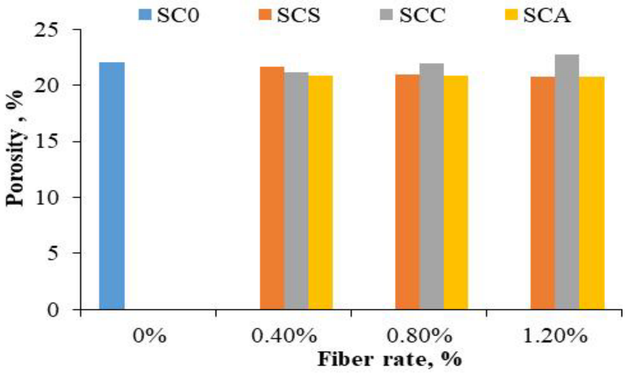


Fig. 14. Variation in water-accessible porosity as a function of recycled fibre content and type

In the SCC mix, the introduction of copper waste fibers at rates of 0.4 % and 0.8 % results in a slight reduction in the water-accessible porosity to 21.12 % and 21.91 %, respectively, compared to the reference concrete. Above and beyond, this may be due to the improvement and uniformity of the internal structure of the concrete. On the other hand, the porosity increases when the fiber rate is high at a rate of 1.2 %, which could be explained by the formation of pores resulting from air trapped around these fibers [45].

More and more, the addition of aluminum waste fibers gave positive results in reducing the porosity accessible to water, whatever their proportion in the mix, until reaching the minimum porosity value at the maximum proportion of 1.2 %. Nonetheless, this can be attributed to a strengthening of the interconnection and bonding of the internal concrete structure [46].

4.11. Water absorption by capillary

Initial observations of the curves in Fig. 15 illustrate that the absorption rate for the reference concrete and the SCS mix evolves slowly, in the same way and with the same dynamics, whatever the level of steel fibers incorporated in the mix. Further, the addition of 04 % and 08 % steel fibers led to a reduction in the capillary absorption coefficient compared with the reference concrete, which is justified by the increased density of the SCS mixes. Nonetheless, it should be noted that the addition of 1.2 % steel fibers increases now and then the absorption coefficient (between 05 and 90 minutes), which may be due to the vertical orientation of certain fibers; in other words, the fibers were aligned in the direction of capillary flow, thus facilitating the water absorption process [11].

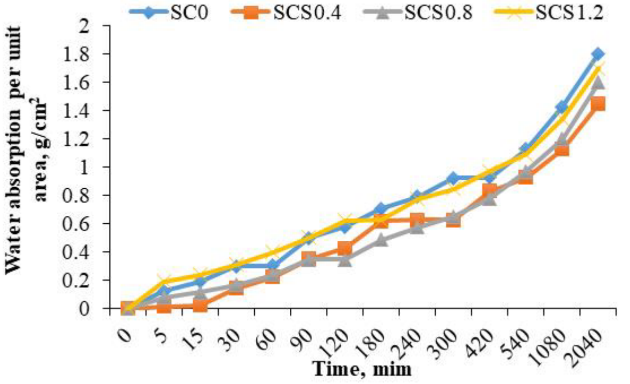


Fig. 15. Water absorbed per unit area as a function of time for the SCS

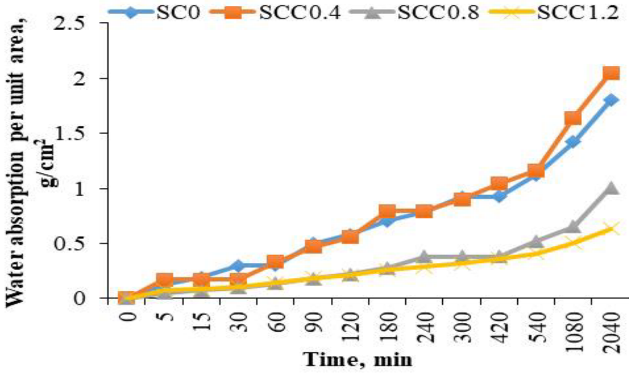


Fig. 16. Water absorbed per unit area as a function of time for the SCC

Incontestably, the capillary absorption coefficient increased with the addition of 0.4 % copper waste fibers (as shown in Fig. 16). As a fact of matter, most of the values obtained have shown to be higher than those of the reference concrete, whereat the maximum absorption coefficient was recorded at 2.051 g/cm^2. However, the negative effect of fibers on the values of the absorption coefficient by capillarity can be attributed to their elasticity, which allows them to easily bind to the concrete [47]. Then, the absorption coefficient decreases with increasing copper fiber content, with the lowest value recorded at 1.2 % copper fiber. In virtue, this decrease is related to the increase in the density of the SCC mixture due to the pozzolanic effect on the physical and chemical properties of the porous structure [43], which prevents bonding between these pores.

The results shown in Fig. 17 demonstrate an increase in the capillary absorption coefficient with the introduction of aluminum fibers into the sand concrete compared with the reference concrete during the period from 0 to 60 minutes of the test. However, this increase continued more than ever in the percentages of 0.4 and 0.8 %. Thus, this is probably due to the shape, length and properties of the fibers, which can increase the length of the interconnected pores [47 – 48].

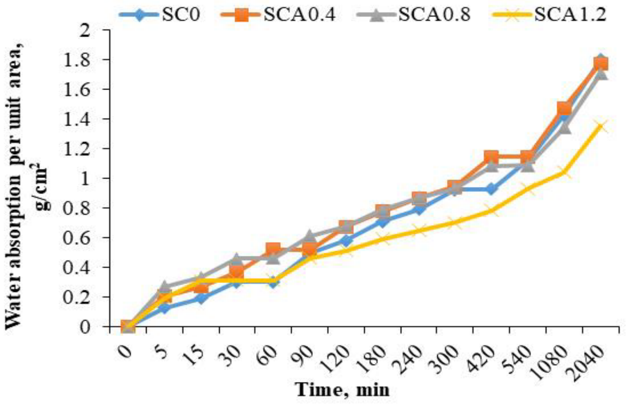


Fig. 17. Water absorbed per unit area as a function of time for the SCA

On the other hand, the effect of the 1.2 % aluminum fiber content after 60 minutes is positive on the absorption coefficient, whereat it decreases compared to the other mixes to reach a maximum value of 1.131 g/cm^2. Consequently, this can be attributed to the strengthening of the interconnection and bonding strength of the internal structure, thus preventing bonding between the capillary pores of the concrete [46].

Comparing the capillary absorption of different concretes, the maximum absorption is given by concrete based on 0.4 % recycled copper waste fibers, whilst the minimum values are recorded in concrete with 1.2 % copper waste fibers.

4.12. Chemical attacks by acids

4.12.1. Attack by sulfuric acid (H_2SO_4)

In the light of the results of the acid resistance tests, measured by the loss of mass due to attack by sulfuric acid H_2SO_4 on the SCS samples (as shown in Fig. 18 a), we can notice that after 03, 07, 14 and 21 days, there was an increase in the loss of weight compared with the reference concrete. However, this is due to the acid attack of the surface layer of the concrete which reacts with the $Ca(OH)_2$ portlandite resulting from the cement hydration [49], forming water-insoluble calcium carbonates that accumulate in the pores, thus causing the concrete to shatter [50]. Nevertheless, after 28 and 56 and 90 days, the weight loss due to sulfuric acid decreases significantly with the addition of 0.8 % and 1.2 % steel fibers up to 7.98 % at 90 days of storage, hence confirming previous results indicating that the addition of steel fibers limits the development and formation of initial cracks, while reducing the concrete porosity [51].

With the same behavior of the SCS mix, the results of the mass loss tests due to H_2SO_4 sulfuric acid attack on the SCC samples (as shown in Fig. 18 b) demonstrate an increase in weight loss compared with the reference concrete up to 21 days, in all proportions. Nonetheless, this is due to the rate of erosion which depends on the rate of penetration of the sulphuric acid into the concrete structure and to reach $Ca(OH)_2$ and $3CaO.Al_2O_3$ [52], as shown by the chemical reactions hereunder Eq. 1 and Eq. 2:

$$H_2SO_4 + Ca(OH)_2 \rightarrow CaSO_4 + 2H_2O; \quad (1)$$

$$3CaSO_4 + 3CaO{\cdot}Al_2O_3{\cdot}6H_2O + 26H_2O \rightarrow 3CaO{\cdot}Al_2O_3{\cdot}3CaSO_4{\cdot}32H_2O. \quad (2)$$

After this, the dynamics of mass loss in the mixture containing 0.8 % copper fibers decreased considerably compared to the other proportions, which had similar or better behavior than the reference mixture, at 28 and 56 days. However, it is important to note that the mass loss in the SCC0.4 % mix also decreases at 90 days to 12.5 %, equivalent to the value for the SCC0.8 % mix. Besides, this improvement in resistance to sulfuric acid attack is due to the increase in concrete density resulting from the addition of fibers that reinforce the porous structure [43].

The incorporation of aluminum waste fibers has a negative effect on resistance to chemical attack and repels the penetration of sulfuric acid (as shown in Fig. 18 c). Above and beyond, the results demonstrate a significant and rapid increase in the mass loss of concrete, regardless of the aluminum fiber content, due to the attack of sulfuric acid on the surface layer of the concrete, causing it to shatter [50]. On the other hand, the shape, length and characteristics of aluminum fibers can alike have a negative impact on the porosity of concrete, thus increasing the length of interconnected pores [47]. However, this can be added to the formation of pores in SCA samples as a result of the potential reaction of aluminium with portlandite $Ca(OH)_2$ [38], which facilitates the penetration and permeability of sulfuric acid through the concrete.

Additionally, it can be said that the effect of waste steel and copper fibers on the resistance to sulfuric acid attack was positive by reducing the rate of weight loss as a function of fiber content within the sand concrete compared to the reference concrete; whereas the effect of aluminium fibers was negative, regardless of their percentage in the concrete.

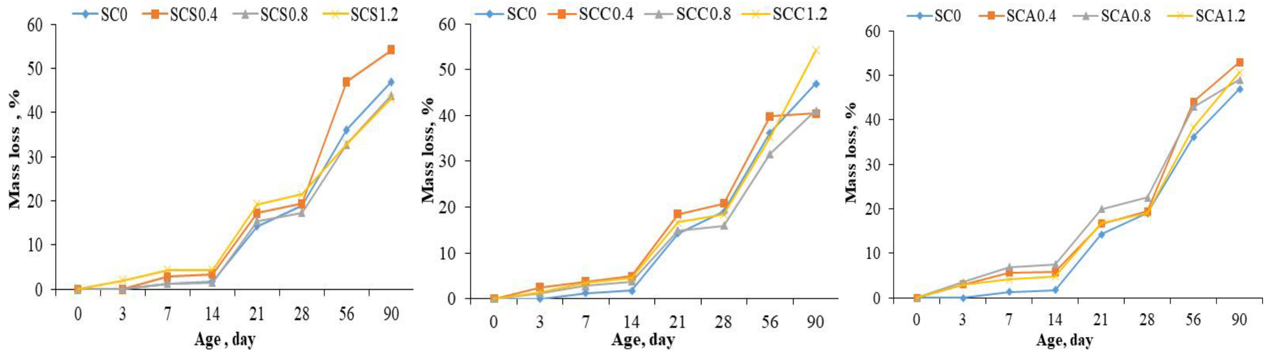
4.12.2. Attack by hydrochloric acid (HCl)

The test results for resistance to HCl acid attack on SCS, SCC and SCA mixes (as shown in Fig. 19) illustrate a loss of mass in all phases and whatever the fiber content used, but it is for all time lower than that of the reference concrete. Nevertheless, this is due to the chemical reaction of hydrochloric acid with the portlandite $Ca(OH)_2$ and the lime $CaCO_3$ released by the hydration of the cement, which produces highly soluble calcium chloride ($CaCl_2$) that is very harmful to concrete. Therefore, this can be explained by the equations hereinafter Eq. 3 and Eq. 4:

$$2HCl + Ca(OH)_2 \rightarrow CaCl_2 + 2H_2O; \quad (3)$$

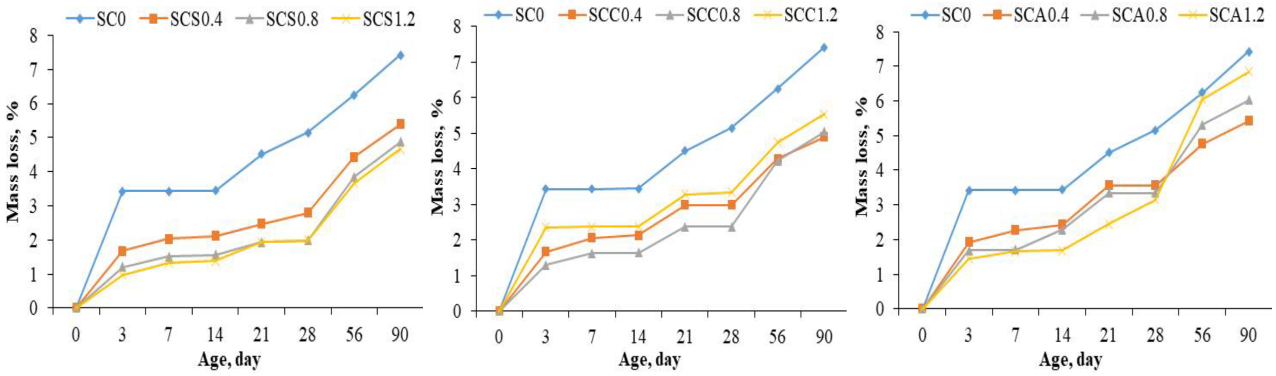
$$2HCl + CaCO_3 \rightarrow CaCl_2 + CO_2 + H_2O. \quad (4)$$

It is evident that increasing the content of waste steel fibers (as shown in Fig. 19 a) reduces in a significant manner the rate of mass loss of the sand concrete studied in all phases.



a b c

Fig. 18. Variation in mass loss for different types of concrete as a function of immersion time in 5%H_2SO_4: a – Sand concrete reinforced by steel fibers; b – Sand concrete reinforced by copper fibers; c – Sand concrete reinforced by aluminum fibers



a b c

Fig. 19. Variation in mass loss for different types of concrete as a function of immersion time in 5 %HCl: a – Sand concrete reinforced by steel fibers; b – Sand concrete reinforced by copper fibers; c – Sand concrete reinforced by aluminum fibers

Further, at a proportion of 1.2 % steel fibers, the mass loss rate decreased by 37.19 % after 90 days of immersion in the chemical solution compared with the SC0% mix, thus confirming the role of steel fibers in reducing concrete pores and limiting the crack development [11].

In the same context, the copper waste fibers helped to limit the penetration of hydrochloric acid into the concrete by reducing the rate of mass loss (as shown in Fig. 19 b). Above and beyond, the proportion of 0.8 % copper fibers can be considered an optimum value, as a 32.07 % reduction in the rate of mass loss was recorded after 90 days. However, this is due to the increase in the density of the SCC mix resulting from the pozzolanic effect on the physical and chemical properties of the porous structure [43], thus preventing the permeability of HCl acid between these pores inside the sand concrete.

Undoubtedly, the same behavior was observed in the SCA mix (as shown in Fig. 19 c), whereas the aluminum waste fibers helped to reduce the loss of mass resulting from hydrochloric acid attack, to a variable extent depending on the fiber content and the duration of immersion in the chemical medium, compared with the reference concrete. More to the point, a 26.95% reduction in mass loss was recorded in the SCA0.4% mix after 90 days. Consequently, this is a direct reflection of the ability of the aluminum fibers to reinforce the cohesion and bond strength of the internal structure of the concrete, thereby limiting the attack of HCl acid [46].

The results demonstrate that waste steel fibers were the most effective in terms of resistance to hydrochloric acid attack compared with the other mixes. Nevertheless, it is important to note that all fibers, regardless of their proportion in the sand concrete, had a positive effect in reducing mass loss.

4. CONCLUSIONS

In the light of the obtained results, several significant conclusions can be drawn, as follows:

1. steel and copper waste fibers significantly increased the density of concrete, whilst aluminum waste fibers reduced it regardless of their proportion;
2. steel fibers improved the workability of sand concrete at proportions of 0.4 % and 0.8 %, whilst it decreased with increasing amounts of copper and aluminum fibers in the mix;
3. the steel fibers improved the compressive strength of the concrete in the long term, whilst the copper fibers improved the short-term and medium-term strengths. On the other hand, aluminum fibers generally reduced the compressive strength at all ages;
4. the introduction of waste steel and copper fibers increased the tensile strength at all ages and at all rates, except in the SCA mix in the short term;
5. the 1.2 % fibers improved the internal structure and homogeneity of the concrete by increasing the sclerometer compressive strength for steel fiber concretes and the ultrasonic wave velocity for copper and aluminum fibre concretes;
6. the dynamic modulus of elasticity of sand concrete increased with increasing proportions of steel and aluminum fibers up to 1.2 %;
7. water absorption by immersion decreased for all proportions of recycled fibers;
8. water-accessible porosity decreased in the SCS and SCA concrete mixes, but increased in the SCC concrete mix with increasing fiber content;
9. the recycled fibers reduced the water absorption by capillary of the sand concrete, particularly with a 1.2 % copper fiber content;
10. the incorporation of steel and copper fibers improved durability and slightly reduced the mass loss of the concrete with respect to H_2SO_4 sulfuric acid attack, whilst aluminum fibers had a negative effect in all proportions;
11. it can be said that steel, copper and aluminum waste fibers prevent the penetration of hydrochloric acid HCl and reduce the mass loss of sand concrete in all proportions.

From this work, we can say that the recycling of blacksmith waste in the formulation of sand concrete has a beneficial effect and encourages research in this area.

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