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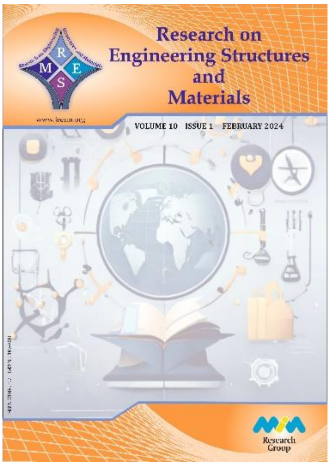

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Research Article

Contribution to the study of an eco-sand concrete containing recycled sands from waste granite and recycled clinker

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Abstract

The reuse of waste materials, particularly granite and undercooked or overcooked clinker, in sand concrete formulation is the focus of this study aimed at conserving natural resources and protecting the environment within the framework of sustainable development. To achieve this objective, we replaced ordinary sand with recycled sands in the sand concrete volume. Specifically, we incorporated granite waste (GS) and recycled clinker (CS) at rates of 20 and 40%. Subsequently, we conducted a series of evaluations on the different formulations. These evaluations included fresh state properties such as density, workability, and air content, as well as mechanical properties like compressive strength, flexural strength, rebound hammer, ultrasonic pulse velocity, modulus of elasticity, and X-ray diffraction (XRD). Additionally, we analyzed durability parameters such as water absorption, dimensional variation, freeze-thaw resistance, acid attacks, and chloride penetration on hardened concrete. We compared these results with reference samples and considered potential correlations among the different parameters. The results obtained showed improvements in workability, hardness, and homogeneity with enhancements in microstructure, with the best results obtained from SCC compared to the control concrete and SCG. The results of mechanical properties demonstrated that concretes containing recycled clinker sand are more resistant in compression and flexural strength compared to SC0 and SCG, with maximum strengths observed in concrete containing 40% recycled clinker at ages 7, 28, and 90 days. Durability parameters were acceptable with slight reductions in ultrasonic pulse velocity and modulus of elasticity after freeze-thaw cycles. A good correlation was observed among the various parameters.

1. Introduction

The increase in the world's population and changing consumer habits have led to a rapid depletion of our natural resources. Moreover, climate change and the accelerated loss of natural resources have given rise to serious environmental problems, especially in recent decades. Therefore, it has become crucial to significantly reduce material consumption and efficiently utilise available natural resources through waste recycling.

Certainly, construction is undeniably one of the sectors with the highest consumption of raw materials. The excessive use of certain aggregates, like sand, in the production of mortar and concrete has resulted in a scarcity of these materials. Meanwhile, waste generated by the industrial and construction sectors, as well as the remnants and debris of

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certain materials that are abandoned in the natural environment, have detrimental effects on the environment.

A great deal of research works has been carried out into the recovery of waste for use as aggregates in mortars and various types of concrete and in particular sand concrete which has been developing in recent years, especially in Algeria. Beyond, the waste in question includes demolition concrete, off-cuts from tiling and ceramics, bricks and breezeblocks, as well as marble and granite waste. In addition, waste from the cement industry, in respect such as sludge, Cement Kiln Dust (CKD) and unbaked or under baked clinker, which is mainly due to errors in controlling the firing phase, temperature fluctuations and kiln stoppages and restarts caused by power cuts, breakdowns or planned stoppages, was used either in the form of fine aggregates or gravel. Further, this recycled waste was then used to partially or totally replace ordinary aggregates in different types of construction materials to assess the impact of recycled aggregates on the properties of such materials in their fresh and hardened states, as well as on their durability parameters.

In this context, the aim objective of this research is to promote the utilisation of granite debris from the construction industry and waste from the cement industry, especially unbaked or under baked, as fine aggregates in the formulation of sand concrete. The objective is to preserve natural resources, minimise waste, and reduce emissions, all of which play a critical role in environmental protection.

Many researchers have been interested in reusing granite off-cuts as a fine powder that partially replaces cement or sand in mortar formulation. Gupta and Vyas [1] studied the feasibility of replacing fine aggregates in a mortar with granite waste fines; thus, they found an improvement in workability, an increase in mechanical performance (compression and tension, ultrasonic pulses and dynamic modulus of elasticity) and durability and in particular adhesive strength, water absorption and drying shrinkage. On the other hand, Suárez-Navarro et al. [2] demonstrated that mixtures containing granite fines gave slightly lower compressive strengths than the reference mortar, whilst the substitution of sand by granite waste fines induced no net difference in flexural strength compared with the control. Moreover, the potential effects of using granite waste on the increased durability of mortar and concrete, including abrasion, freeze/thaw cycles and resistance to sulphate attack were illustrated by the study of Mashaly et al. [3], who alike concluded that granite waste could effectively be used in the production of concrete bricks, paving units and cement tiles. However, Ramos et al. [4] found an improvement in the resistance of mortars to chlorides and alkali-silica reactions by incorporating 10% of granite waste fines as a cement replacement.

Unquestionably, the influence of partial substitution of sand in a concrete by granite waste up to a rate of 25% was the subject of the works conducted by Allam et al. [5] who found a slump of the order of 10cm and a higher compressive strength compared to control concrete at all ages. Likewise, Lakhani et al. [6] observed the same findings, whereat a decrease in slump as a function of increasing the rate of fine granite waste aggregate, which is due to the fine particle size of such waste, as this decrease in workability, could easily be improved with the use of super-plasticizers [7]. More to the point, Vijayalakshmi et al. [8] found that substituting up to 15% of the ordinary sand in concrete with polished granite waste resulted in concrete that met the necessary strength and durability requirements. Nonetheless, they advised that these wastes should be chemically treated to improve their sulphate resistance by undergoing a bleaching process before being added to the concrete mix. Subsequent to which, the results of the works conducted by Singh et al. [9] on the effect of granite cutting waste fine aggregate, on concrete properties, have clearly illustrated that concrete substituted with granite waste exhibits increased resistance to carbonation, chloride ion penetration, acid attack and exposure to elevated temperatures at an optimum granite waste replacement of 25%.

Indeed, granite waste was alike recovered in the composition of self-compacting concrete, seeing that Jain et al. [10] studied the partial substitution of fine aggregates of a self-compacting concrete up to 60% by granite waste powder. The results indicate that the compressive strength in all concrete mixes was higher than the one deduced at of the control except for the mixes with 50% and 60% substitution rate. All the concrete mixes, with the exception of the 60% granite powder mix, demonstrated superior resistance to carbonation, drying shrinkage, chlorides and corrosion compared with the control mix. In the same context Gautam et al. [11] worked on the behaviour of a self-compacting concrete containing granite waste as fine aggregate, they found satisfactory results in the fresh state except for the self-compacting concrete of 40% granite waste fine aggregate, as the maximum resistances are recorded for the self-compacting concrete based on 30% granite waste fine aggregate. Nevertheless, increased resistance to chloride and corrosion was observed for the incorporation of up to 30% fine granite waste aggregate.

Waste from the cement industry, including Cement Kiln Dust (CKD) and unfired or poorly fired clinker, has been used in several types of construction materials. CKD has been employed as a cement additive [12-13-14] and as a component of sand concrete [15]. On the other hand, there has been limited research on the valorisation of baked or unbaked clinker in construction materials. Except for a few in-depth studies have been carried out on the subject, notably the research of Chaib et al. [16], which investigated the impact of baked and unbaked clinker on cement quality, and Kaplan et al. [17], who explored the integration of clinker aggregates into geo-polymer grouts.

Fig. 1. Waste granite and recycled clinker

In the study conducted by Smir [18], the aim was to recover discarded unbaked clinker that the HOLCIM Company had previously considered as waste, along with reusing it in cement production and analysed the impact of this clinker on the quality of the produced cement. In this respect, they found that the workability of concrete made with this cement became increasingly difficult as the addition of unbaked clinker to the cement increased. This was mainly due to the high free lime content of the unbaked clinker and the high-water content associated with the percentage of baked clinker. Hence, this work makes it possible to provide definition to the optimum quantity of unbaked clinker to add to the cement without altering the concrete characteristics. Many studies have demonstrated the advantages of utilising waste clinker and granite, whether in the form of aggregates or cement additives in mortars, concrete, and self-compacting concrete. Therefore, this work aims to use waste granite and recycled clinker unbaked or under baked as shown in Figure 1 to partially replace ordinary sand. These recycled sands are incorporated into sand concrete with substitution rates of 20% and 40%. The study examines the impact of these recycled sands on the properties of the concrete in its fresh state, as well as its mechanical performance in the hardened state, durability, and microstructural parameters.

2. Materials

The materials used in the study include a composite Portland cement CPJ-CEM II 42.5 (S-L) sourced from the cement factory of Hadjar Essoud in Skikda, Algeria, with an absolute density of 3.22 g/cm^3. Other components comprise dune sand (DS) of siliceous nature from Oued Z'hor quarry, Skikda-East of Algeria, sand from granite waste (GS) obtained through crushing and sieving granite waste, and recycled clinker sand (CS) obtained by crushing and screening baked or unbaked clinker from the Hadjar Soud cement factory in Skikda (Fig. 2). Additionally, fine limestone (F) retrieved from the filters of the Ben Azzouz quarry in the East of Skikda, passing more than 80% through an 80µm sieve, is included. Table 1 provides an overview of the various physical and chemical properties of the aggregates and the particle size distribution is illustrated in Figure 3. The mix incorporates a super-plasticiser (SP), namely the high-water reducer Master Glinuim 26, as a light brown liquid with a pH of 5 and a density of 1.07 g/cm^3. Finally, tap water at a temperature of 28°C is utilised for the mixing process.

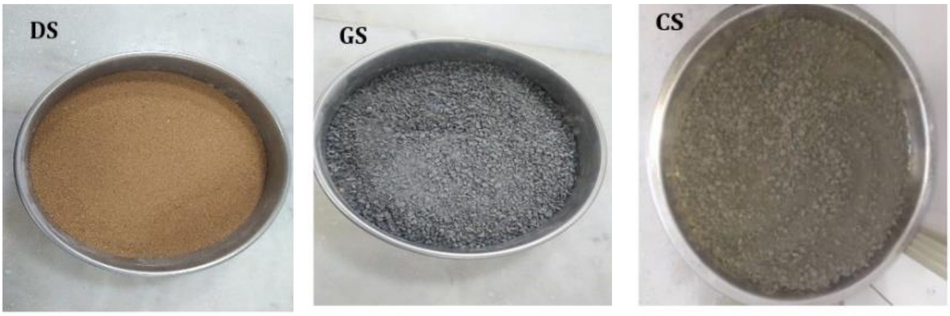

Fig. 2. The sands used

Characterization tests have revealed significant differences among various sands used in concrete production. Granite waste sand exhibits a higher density compared to dune sand and clinker sand. According to Figure 3, the sands used demonstrate satisfactory fineness, with all particles having a size greater than 0.063 mm. In terms of volume, it is observed that (7.33%, 10.67%, and 9.33%) of the particles are less than 0.125 mm, while (93.33%, 26%, and 19.33%) by volume are less than 0.5 mm for the DS, GS, and CS samples respectively. A relatively small percentage, ranging from 6 to 9%, represents particles smaller than 0.063 mm. The grain size distribution curves of the sands used are continued, and the particle size distribution according to the NF EN12620 and NF P18-545 standards shows that the curve of the granite waste sand (GS) exhibits the best regularity of grain size compared to the recycled clinker sand (CS) and the dune sand (DS), respectively.

According to the fineness modulus, ordinary sand is finer than granite waste sand and clinker sand respectively. Hence, the introduction of the latter into concrete adversely affects workability and increases mechanical strength. Additionally, granite waste sand contains a higher fines content than dune sand and clinker waste sand. Sand equivalent tests confirm that all sands fall within the 70% to 80% cleanliness range, making them suitable for high-quality concrete production. According to chemical analysis (Table 1), dune sand and sands from GS and CS contain a percentage of silicon dioxide (SiO_2) of (77.86%, 41.2% and 22.02%) respectively.

Table 1. Physical and chemical properties of sands

Physical properties			
	DS	GS	CS
Apparent density (g/cm^3)	1.412	1.650	1.489
Absolute density (g/cm^3)	2.631	3.062	2.723
Sand equivalent (%)	74.59	72.34	70.50
Water absorption (%)	1.02	1.67	5.44
Fineness modulus (%)	1.55	3.47	3.90
Inter-granular porosity (%)	46.33	46.11	45.32
Fines content (%)	6	8.33	6.66
Chemical composition (%)			
	DS	GS	CS
SiO_2	77.86	41.2	22.02
Al_2O_3	2.05	13.2	5.49
Fe_2O_3	1.13	9.59	3.72
CaO	4.78	9.06	65.58
MgO	0.19	4.99	1.05
SO_3	0.00	0.31	0.07
K_2O	0.59	0.08	0.90
Na_2O	0.19	2.5	0.20
Cl^-	-	0.01	0.01

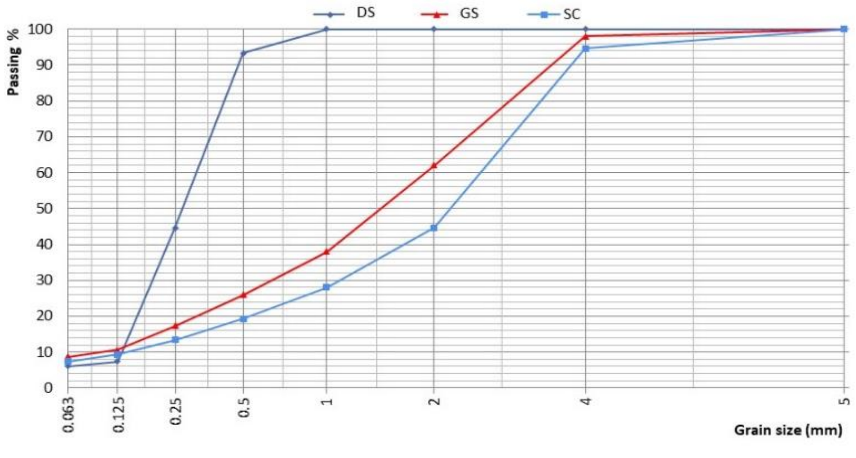

Fig. 3. Particle size distribution of sands

SiO_2 is the dominant compound in the composition of granite; thence silica reacts with lime during the hydration of cement and favours the formation of hydrated calcium silicates, which can slow down the hardening process and make it possible to obtain high resistance in the medium and long term and improve the durability of concrete, particularly in aggressive environments. Furthermore, in addition to silica, granite waste sand contains alumina Al_2O_3 (13.2%), which contributes to the setting of concrete, but has a negative effect on chemical stability and favours attack by sulphates [19]. Conversely, clinker is basically composed of CaO, and the presence of this element promotes the formation of

C3S, which offers high short-term resistance and increases cohesion. Further, the high reactivity increases the homogeneity of the mix and reduces the porosity and permeability of the concrete [19-20].

3. Experimental PROGRAMME AND TESTS METHODS

3.1 Experimental Program

In the experimental programme, we partially substituted in the volume of an ordinary sand (DS) of a sand concrete by recycled sands (granite waste (GS) and recycled clinker (CS)) with replacement rates of 20% and 40%, and studied the effect brought by the introduction of these sands on fresh and hardened properties as well as durability parameters. The SC0 reference formulation was established according to the experimental method of Sablocrete [21] with the fixed parameters being the Water/Cement ratio (W/C=0.68), the cement dosage, the dosage of limestone fines and the content of 1% super-plasticizer. Therefore, the selected formulations (SCG, based on granite waste sand, and SCC, based on recycled clinker sand) are obtained by the same method, with the substitution of ordinary sand by volume with recycled sand. The different compositions of the mixes are illustrated in Table 2.

Table 2. Mix proportions of different concrete mixtures

Mixtures	CEMII (Kg)	DS (Kg)	F (Kg)	SP (Kg)	W (Kg)	GS (Kg)	CS (Kg)
SC0	400	1160.40	252	4.32	272	0	0
SCG 20	400	928.32	252	4.32	272	271.968	0
SCG 40	400	652.72	252	4.32	272	543.936	0
SCC 20	400	928.32	252	4.32	272	0	253.837
SCC 40	400	652.72	252	4.32	272	0	507.674

3.2 Tests Methods

3.2.1 Fresh Properties Tests

The fresh density was evaluated after casting using an 8-liter container, in accordance with standard NF EN12350-6, workability measured by slump with an Abrams cone in accordance with standard NF EN12350-2, and the content of occluded air measured by a concrete aerometer in accordance with standard NF EN12350-7.

3.2.2 Mechanical Properties

3.2.2.1 Mechanical Resistance

Specimens of size (4×4×16) cm^3 preserved in water 28 days until the curing periods of 7, 28 and 90 days, broken in tension by 3-point bending and subsequently in compression in accordance with standards NF EN12390-5 and NF EN12390-3 respectively. The loading should be applied continuously until the specimen ruptures. The elastic modulus of concretes was evaluated at 28 days according to Eq. (1) [22].

$$Ed = \frac{\rho . V^2 (1+\nu)(1-2\nu)}{(1-\nu)} \tag{1}$$

Where: Ed is the dynamic modulus of elasticity (GPa); ρ is the density of the hardened concrete (kg/m^3); V is the ultrasonic velocity (km/s); and ν is the Poisson's ratio.

3.2.2.2 (UPV) Test and The Sclerometer Test

Specimens measuring (15×15×15) cm^3 were prepared for the ultrasonic pulse velocity (UPV) test and the sclerometer test after 28 days of water curing. The sclerometer test, conducted in accordance with standard NF EN 12504-2, evaluates the surface hardness of the concrete through rebound measurements. This method involves striking the concrete surface with a hammer and then measuring the rebound distance. Simultaneously, the UPV test, performed according to standard NF EN 12504-4, used a portable digital ultrasonic tester. This method involves transmitting ultrasonic pulses through the concrete sample, allowing for the determination of its velocity.

3.2.3 Durability

3.2.3.1 Shrinkage and Swelling

Measured on specimens measuring (4×4×16) cm^3 fitted with studs. Shrinkage specimens are stored in air, whilst swelling specimens are stored in water in accordance with standard NF P 18-427. The shrinkage and swelling are measured using a deform meter equipped with a comparator and reference rod, enabling measurements with an accuracy of less than or equal to 0.005 mm. A 270 mm long rod is used to calibrate the deform meter.

3.2.3.2 Water Absorption by Immersion

According to Neville [22], the specimens of dimension (5×5×5) cm^3 are kept in water for 28 days. The specimens are weighed to determine the wet mass, after which they are placed in the oven at 105± 3°C until a constant mass is obtained, then they are weighed to determine the dry mass, the absorption is measured by subtracting the dry mass from the wet mass, then dividing by the dry mass.

3.2.3.3 Water-Accessible Porosity

Is measured on specimens measuring (5×5×5) cm^3, which are kept in water for 28 days according to the NF P18459 standard. After this curing period, the saturated mass is measured, followed by the use of a hydrostatic balance to measure the hydrostatic mass. Subsequently, the samples are dried at 105°C until reaching a constant mass, after which their dry mass is measured. The porosity is calculated from the ratio between the difference between the saturated and dry masses and the saturated and hydrostatic mass, with the value expressed as a percentage.

3.2.3.4 Capillary Water Absorption and Sorptivity Test

The test was conducted in accordance with the NF EN 13057 standard using specimens measuring (7×7×28) cm^3. These specimens were immersed in water for 28 days before testing. Their side faces sealed and they were then subjected to unidirectional water absorption from their bottom for nearly a week. This procedure was carried out to determine capillary absorption, which was plotted against the square root of the elapsed time to yield the sorptivity.

3.2.3.5 Freeze-Thaw

On specimens of size (4×4×16) cm^3 fitted with studs are subjected to 300 freeze-thaw cycles in accordance with standard NF P18-425. Shrinkage and mass measurements were taken every 30 cycles. An ultrasonic test was carried out at the end of the test.

3.2.3.6 Chloride Penetration

According to NT BUILD 492-1, on (4×4×16) cm^3 specimens kept 28 days in water at a temperature of 20 ± 2°C. Thereafter, totally immersed in a prepared saline solution of sodium chloride (5% NaCl) diluted in distilled water for 120 days, the specimens underwent a process of cutting and application of a silver nitrate solution ($AgNO_3$) with 0.1 M concentration onto their concrete surfaces.

3.2.3.7 Chemical Attack by Acids

After 28 days of curing in water, the specimens of dimension (5×5×5) cm^3 are weighed to determine an initial mass, then they are immersed in solutions with a concentration of 4% hydrochloric acid (4% HCl) and 4% acetic acid (4% CH_3COOH) added to the water volume. The chemical resistance is evaluated by measuring the mass loss of the specimen according to ASTM C267-96 standard. The specimens are cleaned three times with fresh water to remove the deteriorated concrete and left to dry for 30 minutes. Then they are weighed again. This operation is performed after 7, 14, 21, 28, 56, 60, 90, and 120 days of immersion. The solutions used are renewed every 14 days (based on the pH variation).

3.2.4 Microstructural Analysis Tests

A materials characterization technique uses X-rays to determine its crystalline structure. X-rays are directed towards a sample, which diffracts them in different directions depending on its crystalline structure. By measuring the angles of X-ray diffraction, the arrangement of atoms in a sample can be determined, thus obtaining information about its crystalline structure. The determination of amorphous and crystalline phases by X-ray diffraction was carried out using an XRD diffractometer (Philips, X'Pert) using Cu Kα radiation, 40 kV, 35 mA, with a step of 0.02° ranging from 10° to 80°. ICDD plots were used to identify the intensity and location of peaks.

4. Results and Discussion

4.1. Fresh State Properties

Figure 4 shows that the fresh densities of ready-mixed concrete increase with increasing levels of recycled sand substitution. Besides, the highest density is obtained for concrete based on 40% granite waste sand (SCG40). Further, it exceeds the value shown by the control concrete of 9.16% and that of the concrete containing 40% clinker waste sand of 4.38%. However, this increase in density is expected because recycled sands have higher absolute densities, higher quantities of fines filling the available voids between the concrete constituents and higher water absorption coefficients than ordinary sand. Therefore, these results are compatible with those found by Abukersh and Fairfield [23] and Kherraf et al. [24] and contrary to those obtained by Shamsabadi et al. [25]. This difference in results may be linked to the different particle distribution and the method of obtaining recycled sand.

The partial replacement of ordinary sand with recycled sands GS and CS results in an increase in workability, with the maximum value achieved by SCG40 concrete, exceeding that of SCC40 concrete by 17% and that of the control concrete by 27%. Besides, this improvement may be attributed to the better particle size distribution of GS on one hand. In the other hand, the finer particle size, which contributed to reducing inter-particle friction within the cement matrix due to the rough and angular morphological characteristics of granite, which can enhance interlocking between particles and improve cohesion within the concrete mixture. This improved particle packing can lead to a reduction in voids and improve the overall compactness of the concrete, thereby increasing its workability [26-27]. These results contradict those found by Zhang et al. [28].

The volumes of content air in clinker sand-based concretes are slightly higher than those in concretes containing granite waste sand. In this respect, the recorded increases in occluded air volume compared with the control concrete were 19.61% for SCG40 and

27.45% for SCC40 concretes. Moreover, this increase in the volume of air occluded in concretes based on recycled sands is certainly linked to the morphology of these grains, which traps air bubbles in the cement matrix of the concretes [29-15].

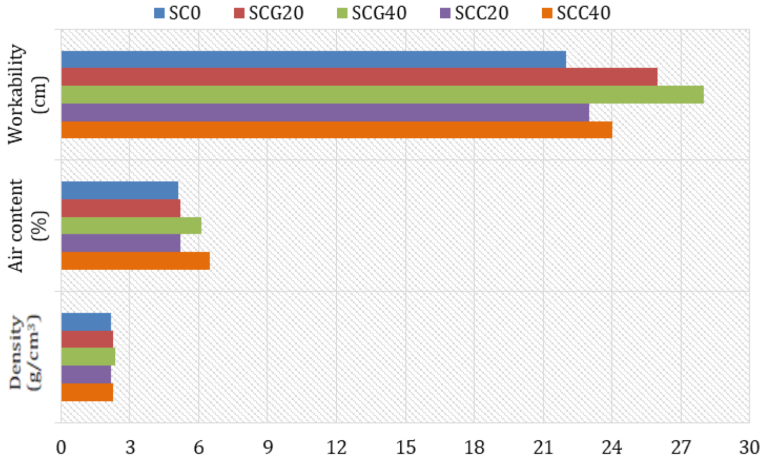

Fig. 4. Variation in fresh properties as a function of substitution rate and sand type

4.2. Mechanical properties

4.2.1. Compressive Strength

The results demonstrated that the increase in strength was observed with the use of GS and CS as partial sand substitution compared with the reference concrete (Fig. 5). Maximum strength was observed for the SCC40 mix at all curing periods. The increase in strength of the mixes after inclusion of 20% and 40% GS was observed. Nonetheless, this increase in strength could be attributed to the finer size of GS; the better filling effect of the particles also reduces interconnected voids and improves the density of the concrete matrix, which improves the compressive strength of the concrete up to an optimum percentage of granite waste [30].

In addition, the roughness and irregular shape of the granite particles increases the strength, as these particles gave better adhesion which results in better bond development between cement paste and aggregate [31-32]. Furthermore, a similar strength gain trend has alike been observed by several researchers Singh et al. [33] and Ghannam et al. [34] who have used granite as a fine aggregate replacement with an optimum range of 10% to 30% in concrete. Increases in the strengths of SCC mixes as a function of the increase in the substitution rate. Besides, this increase is explained by the hydraulic power of the fine CS particles, on the one hand. However, this increase in strength is a consequence of the increase in compactness, on the other hand, due to a pozzolanic reaction developed by the reactive fines contained in the CS [35-36]. In virtue of which, our results contradict those obtained by Prošek et al. [37]. At 28 and 90 days, concretes based on recycled clinker sand give the best compressive strengths compared with concretes based on granite waste sand. Nevertheless, this is due, on the one hand, to the fineness modulus of the CS sand and, on the other hand, to the presence of CaO, which provides a lot of C3S, an element responsible for strength and cohesion [20-38]. There was a good linear correlation (Fig. 6) between compressive strength and density in the hardened state for all the studied concretes, which indicates the accuracy of the results.

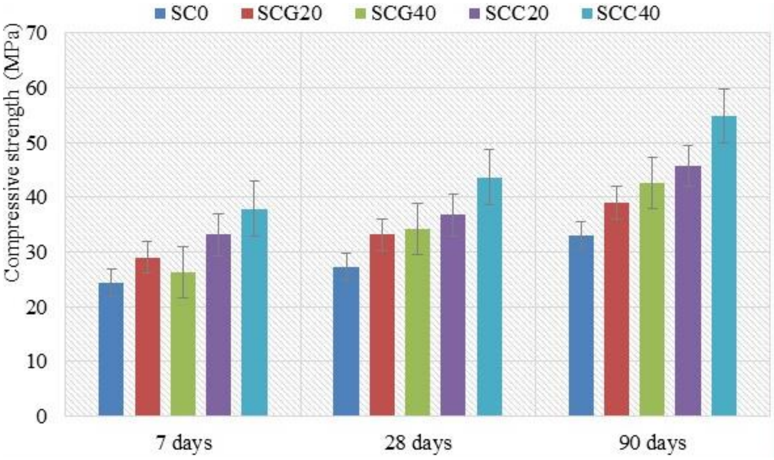

Fig. 5. Influence of substitution rate and type of sand on compressive strength

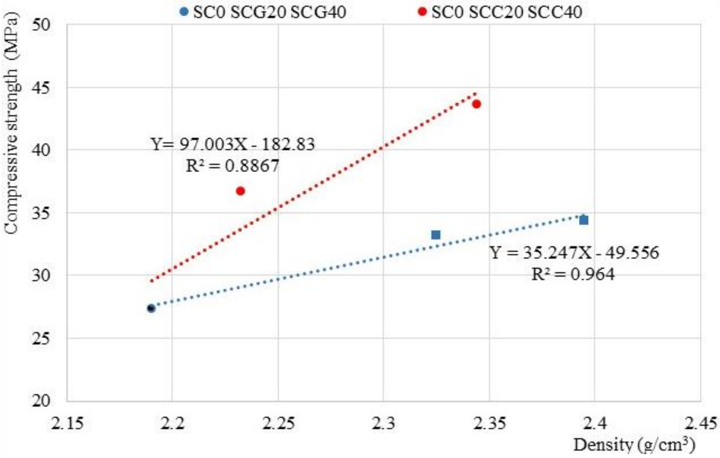

Fig. 6. Correlation between compressive strength and density

4.2.2 Flexural Tensile Strength

At the three timescales of 7, 28 and 90 days (Fig. 7), the flexural tensile strengths of the recycled sand-based concretes were better than those of the control concrete. Besides, SCC40 showed the highest strength, with an 82% increase over the reference concrete. In this respect, these results can be explained by the fact that CS is characterised by sharper, more porous grains, which form stronger bonds with the cement paste in the mix [37]. When they react with the cement minerals and water, the anhydrous components of clinker create hydrates that decrease the porosity of concrete and increase cohesion [20]. These components fill the voids between particles, leading to denser matrices and increased flexural strength. In virtue of which, these results have shown to be consistent with those found by Mebarkia et al. [39].

An increase in flexural tensile strengths was observed in the GS-based concretes compared to the reference concrete, this improvement is due to the rough texture of the granite sand which could have improved the adhesion of the aggregates to the cement paste [40-41]. Figure 8 presents a precise linear correlation between the compressive strength and the flexural tensile strength for all the concretes studied with a correlation coefficient of (0.9557 and 0.9978) for SCG and SCC respectively, which denotes the precision of the results.

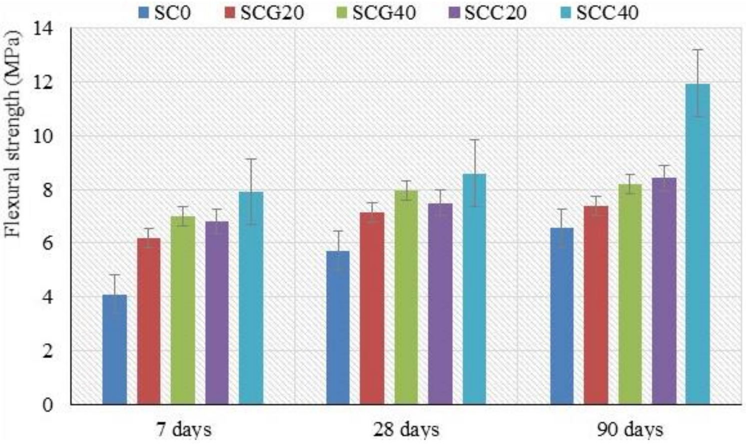

Fig. 7. Influence of substitution rate and sand type on flexural tensile strength

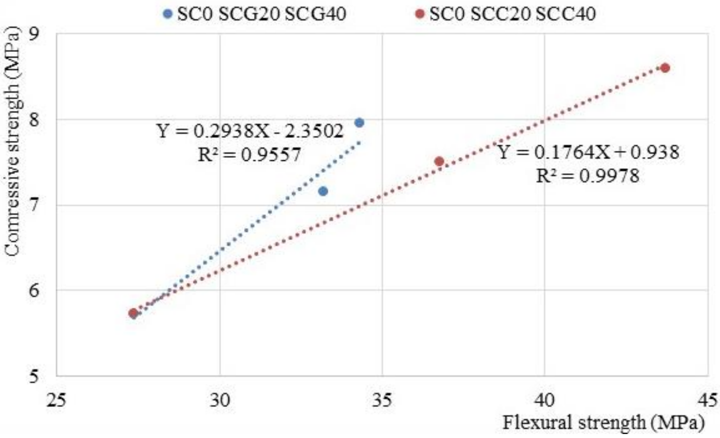

Fig. 8. Correlation between the compressive strength and the flexural tensile strength

4.2.3. Compressive Strength Obtained by Sclerometer

Figure 9 shows that the introduction of recycled sand into the sand concrete increased the surface hardness compared with the control concrete. However, the addition of granite waste sand has a positive effect on surface hardness. Further, compressive strength increases with increasing GS substitution rate to reach a maximum value of 31.40 MPa in SCG40 concrete, this is explained by the fact that granite waste sand contains a lot of silica (41.2%) which gives high medium and long-term strengths. The addition of recycled clinker sand at a rate of 40% gives the maximum strength obtained by sclerometer, the fact of which is explained by the presence of CaO in the clinker sand, which gives good bonding of the aggregate matrix [20]. Definitely, resistances based on recycled clinker sand are higher compared to concretes based on granite waste sand, which may be due to the chemical composition of the clinker, which is close to the chemical composition of the cement.

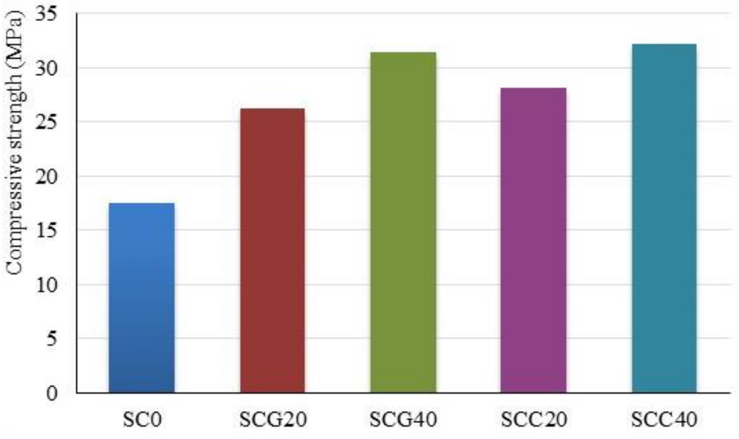

Fig. 9. Compressive strength obtained by sclerometer test

Figure 10 shows the variation in the Schmidt hardness index of the mixes as a function of the type of concrete. However, it shows a precise linear correlation between the two factors with a correlation coefficient of (0.966 and 0.923) for SCG and SCC respectively. Besides, it is clear that the rebound index of concrete made from recycled waste is higher than that of control concrete; it increases with the increase of the substitution rate for the two types of concrete SCG and SCC. In virtue of which, the maximum value of the Schmidt hardness index is given by SCC40.

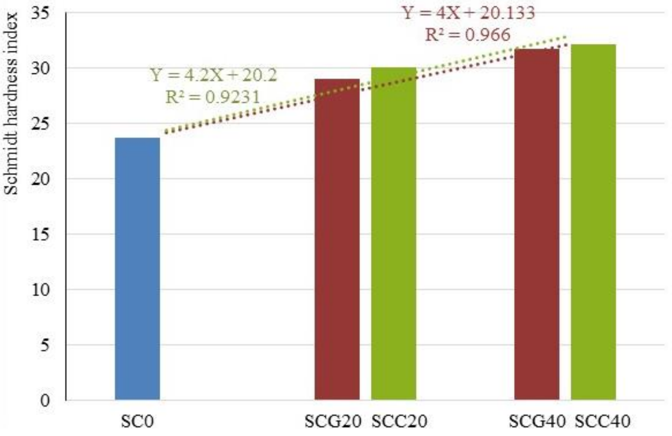

Fig. 10. Variation of the Schmidt hardness index as a function of the substitution rate and type of sand

The correlation between Schmidt hardness index and compressive strength measurements obtained by destructive testing is demonstrated in Figure 11. However, this correlation is established by a linear relationship, with a coefficient of (0.9656 and 0.9627) for SCG and SCC respectively. On the other hand, the Schmidt hardness index values given by the recycled clinker-based concrete have shown to be better than those obtained by the control concrete and the granite waste-based concrete, giving the best strengths. In virtue of which, these results once again confirm that the two SCC20 and SCC40 mixes are the most resistant.

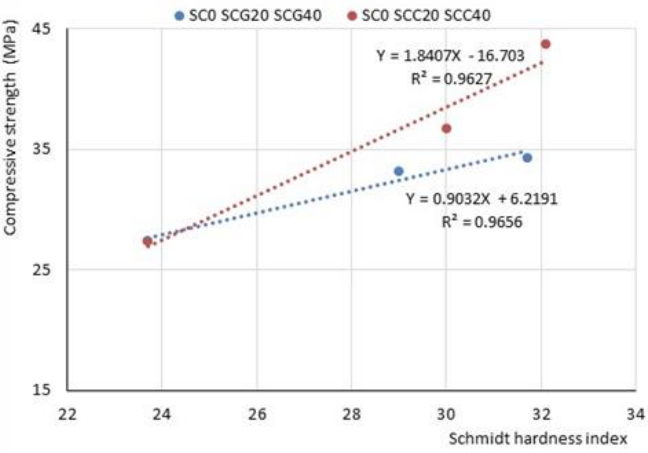

Fig. 11. Correlation between compressive strength obtained by destructive testing and Schmidt hardness index

4.2.4. Ultrasonic Velocity

In fact, the introduction of recycled sand as a partial replacement for ordinary sand leads to an increase in the ultrasonic velocities of the mixtures, whatever the rate and type of sand (Fig. 12). Above and beyond, clinker sand-based concretes showed the highest velocities compared to GS based concretes, these results are explained by the denser structure of CS based concretes compared to GS based concretes. Thereof, these results are in agreement with those found by Sharma et al. [42] and Abbaszadeh and Modarres [43].

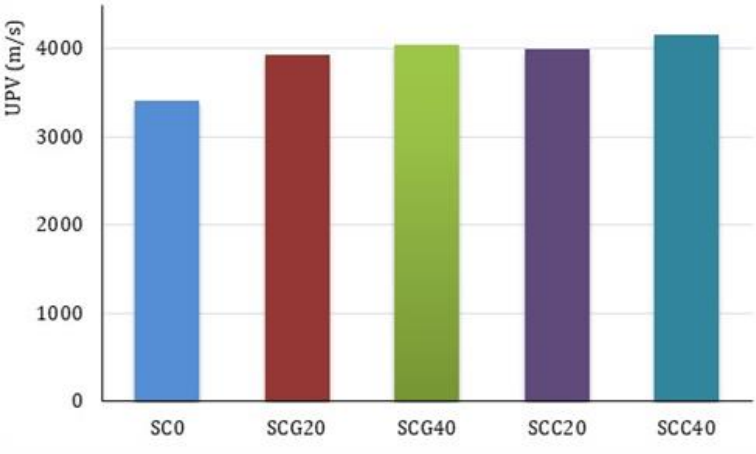

Fig. 12. Variation in UPV as a function of substitution rate and type of sand

4.2.5. Compressive Strength Obtained by The Combined Method

As a fact of matter, the strength of mixes based on recycled sands obtained by the combination of sclerometer and ultrasound (Fig. 13) increases with the increase in the recycled sand content and CS-based mixes give high strengths compared with GS-based mixes. As consequence, the strengths obtained by the combined method are compatible with the strengths obtained by destructive testing, UPV and sclerometer.

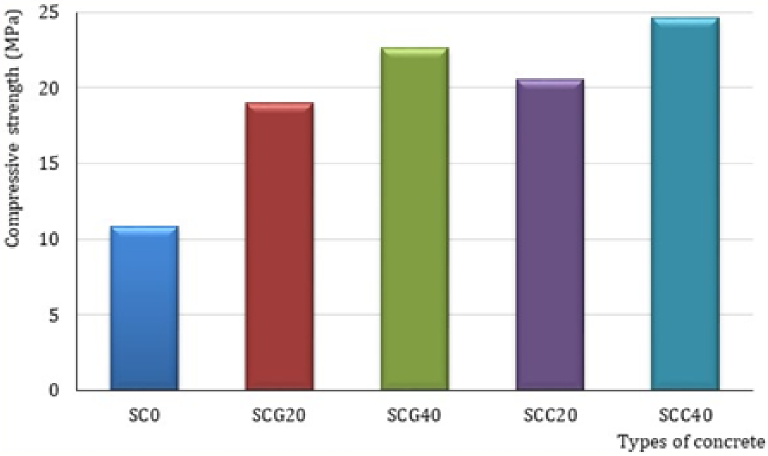

Fig. 13. Compressive strength obtained using the combined method

4.2.6. Shrinkage and Swelling

Indeed, Figure 14 clearly shows that the incorporation of recycled sand from clinker and granite waste has a considerable impact on the total shrinkage of the concretes. After 120 days of conservation, the average total shrinkage values of all the recycled concretes, based on 20% and 40% CS and GS respectively, are higher than those recorded for the reference concrete. Therefore, the result illustrated by the control concrete may be attributed to the more regular filling capacity of the dune sand.

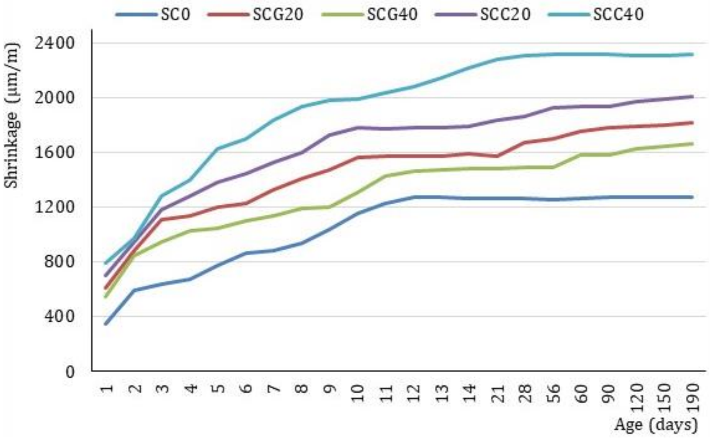

Fig. 14. Influence of substitution rate and type of sand on shrinkage

Likewise, it can alike be noticed that the shrinkage of concrete containing recycled clinker sand is higher than the one of the other types of concrete. In fact, the maximum value is obtained by SCC40 concrete. However, this is due to the evaporation of water trapped in the sand grains, which have a porous microstructure. In addition, this sand contains fine reactive particles that take part in the hydration reaction, resulting in an increase in the volume of the paste and accordingly an increase in the number of micropores filled with free water, which disperses during air-drying. In reality, analysis of the results obtained (Fig. 15) shows that concretes based on granite waste sand and recycled clinker have lower swellings than the reference concretes. In fact, the introduction of granite sand into the mixes produces the lowest swelling values. This is linked to the fines content of the sands, which enclose the existing interstices in the mixes.

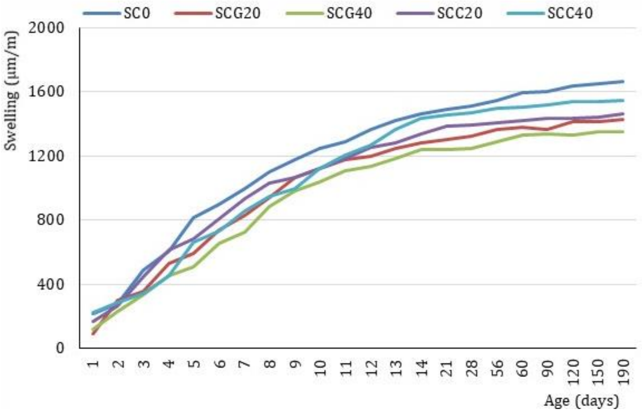

Fig. 15. Influence of substitution rate and type of sand on swelling

4.2.7. Absorption by Immersion

Generally speaking, concretes based on recycled sand have a lower absorption than control concrete (Fig. 16), as this can be explained by their absorption coefficients, which are lower than those of ordinary sand. Nonetheless, substituting ordinary sand with 40% recycled granite waste sand and clinker resulted in a reduction in absorption of 3.9% and 10% respectively.

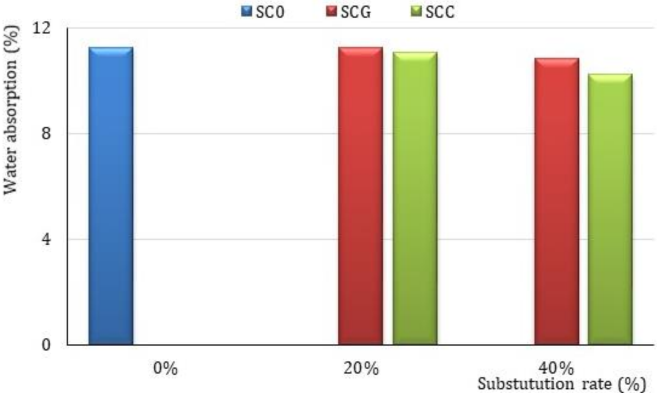

Fig. 16. Water absorption by immersion as a function of the rate of sand substitution and type

Moreover, concrete based with waste granite sand absorbs more water than concrete made with recycled clinker sand. This is due to the hydrated products formed by the addition of CS, particularly the entanglement of C-S-H gel, which gives strength to SCC and develops on the surface of unhydrated grains, gradually filling the capillary voids between the grains and resulting in densification of the matrix. This explains the lower water absorption of SCC compared to SCG (Granite Sand Concrete) [24]. As consequence, these results have shown to be consistent with those found by Ahmadi et al. [44] and Ghorbani et al. [45].

4.2.8. Porosity Accessible to Water

The values of the porosity accessible to water after 28 days of curing are illustrated in Figure 17. Therefore, the results show an increase in porosity when granite waste sand is incorporated, i.e. an increase of 5% compared with the control concrete at a substitution rate of 40%. This increase in porosity is due to the presence of fines in the granite and additional porosity at the Interfacial Transition Zone (ITZ) between the smooth faces of the granite grains and the cement matrix [46]. On the other hand, there was a reduction in porosity when ordinary sand was replaced by recycled clinker sand. Nonetheless, this reduction is of the order of 8.5% at a replacement rate of 40%. In fact, the use of reactive fines made it possible to densify the cement matrix, giving rise to new hydration products and greater compactness, accordingly.

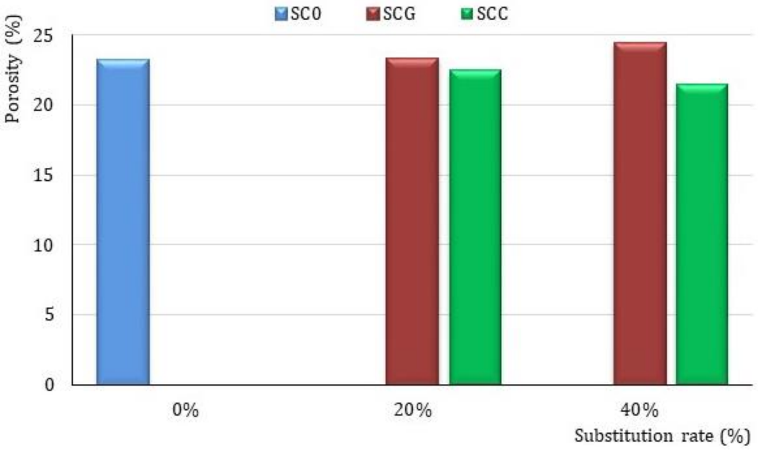

Fig. 17. Porosity accessible to water as a function of the rate of sand substitution and type

4.2.9. Capillary Absorption and Sorptivity

According to the curves in Figure 18, three phases can be observed. The first phase is linear, extending only over the first five hours, and corresponds to the filling of the widest capillaries that water penetrates first. A second linear phase but with a steeper slope extends for about 8 days after the first phase, corresponding to the saturation of narrower capillaries that require more time to fill. In the end, all capillaries tend towards saturation [47]. Indeed, the concrete containing 20% recycled clinker sand performs the best, with the absorbed water mass being 14.89% lower than that of the control. On the other hand, concretes incorporating 20% and 40% granite waste sand show greater capillarity, their capillary absorption coefficients exceeding the one pertaining to the control by 08.36 and 15.5% respectively. Nonetheless, this indicates that the pores in the granite waste sand concrete matrices are large and interconnected compared to those in the control and recycled clinker sand concretes. As consequence, these results have shown to be in agreement with Cheah et al. [48].

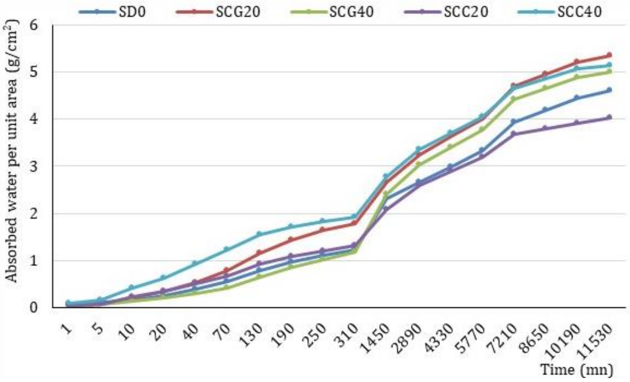

Fig. 18. Influence of substitution rate and type of sand on water absorption by capillarity

The sorptivity coefficient is a parameter closely linked to water absorption by capillaries, as well as to porosity and pore interconnectivity. Figure 19 presents the sorptivity coefficient for the examined concrete mixtures. The sorptivity coefficient was found to be directly proportional to the capillary water absorption of each concrete mixture. Concrete mixtures based on 20% recycled clinker SCC20 performed better than the other mixtures. It can be inferred that the sorptivity coefficient of concretes based on waste granite decreases as the substitution rate increases. Singh et al. [49] showed that water absorption and sorptivity of concrete decrease with an increase in the proportion of granite, which contradicts the results of Pereira et al. [50].

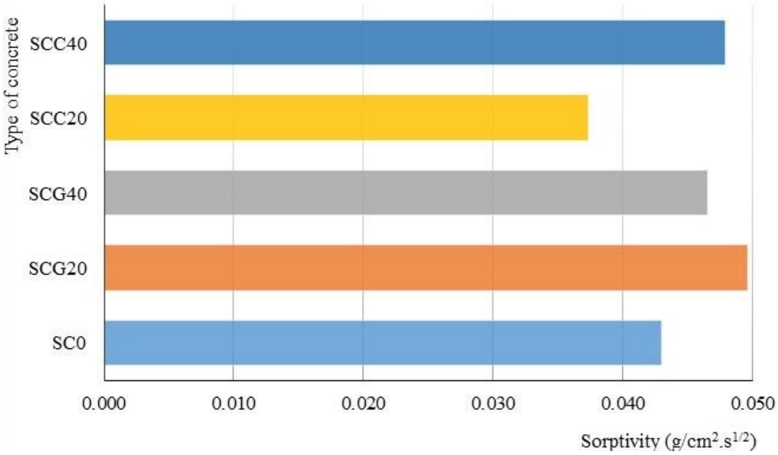

Fig. 19. Coefficient of sorptivity

4.3. Behaviour of Different Concretes Exposed to The Freeze-Thaw Cycle

4.3.1. Freeze/Thaw Shrinkage

It is clear that the shrinkage of the recycled sand-based concretes is less than that of the control (Fig. 20). Besides, all the mixes underwent shortening during the initial cycles, but after reaching 120 cycles, there was no further change in length. Further, the dimensional variation of the SCG20, SCC20 and SCC40 concretes was found to be less than 500 µm/m, indicating a high level of resistance to freeze/thaw cycles as defined by ASTM C 666. These results are in line with those of Zhang et al. [28].

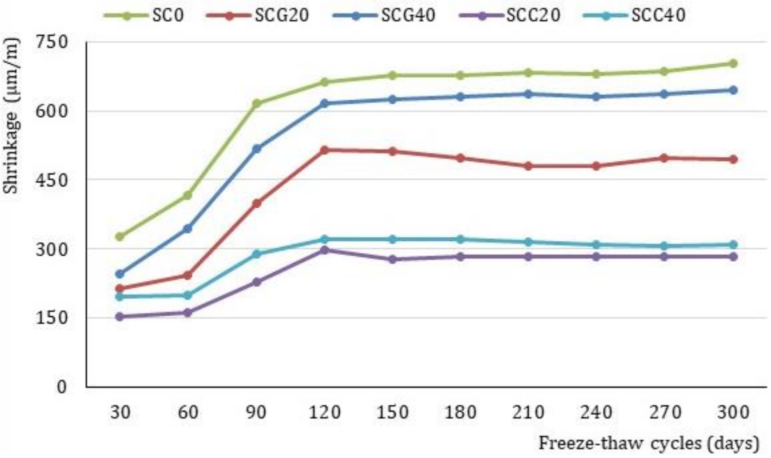

Fig. 20. Dimensional variation as a function of the number of freeze/thaw cycles

*4.3.2. Mass **L**oss*

Figure 21 shows the variation in weight of the concretes tested after 300 freeze/thaw cycles. Further, it is important to note that during the period from 30 to 120 cycles, the SCG40 concretes, as well as the SCC20 and SCC40 concretes, showed a gain in weight. On the other hand, the SCG20 concrete and the control sample lost weight. Beyond 120 cycles, there was no change in mass for the SCG40 and SCC40 concretes. Nevertheless, the SCG20, SCC20 and control concretes experienced a significant loss of mass. Therefore, the maximum loss was for concrete made with 40% granite waste sand.

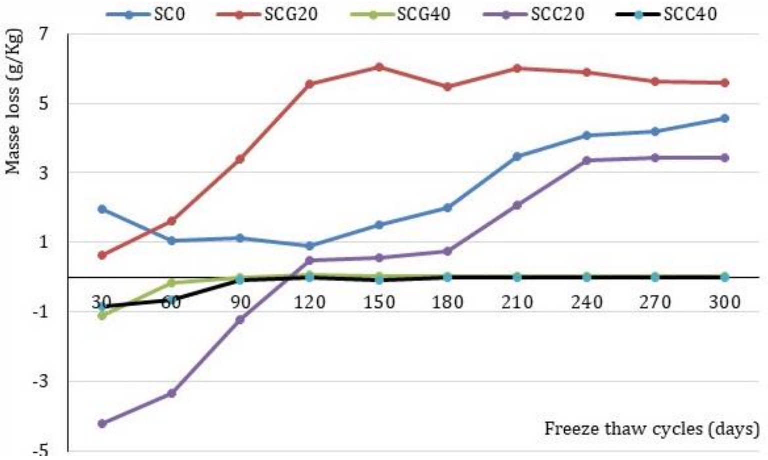

Fig. 21. Mass loss as a function of the number of freeze/thaw cycles

4.3.3. Visual Observation of Deterioration

When concrete freezes, the process of transforming confined pore water into ice can potentially create significant pore pressure. Subsequent to which, this can lead to cracking, spalling and degradation of the concrete. Besides, a visual inspection was carried out to assess any visible signs of cracking and spalling of the surface of the samples following freeze/thaw cycles. According to Figure 22, the SC0 and SCG20 concretes showed good resistance to freeze/thaw cycles, but more or less significant degradation occurred in the SCC20 and SCC40 concretes, whilst the SCG40 concrete showed slight surface brittleness. However, these degradations are due to the poor adhesion between the dune sands and the recycled sands [43].

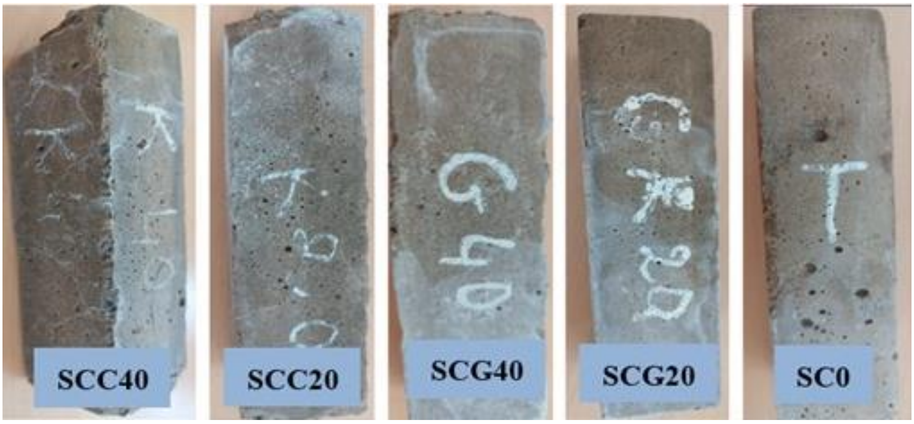

Fig. 22. Visual observation of concrete samples after freeze/thaw cycles

4.3.4. Ultrasonic Speed

In general, the ultrasonic velocities obtained on concretes after exposure to freeze/thaw cycles (Fig. 23) are lower and follow the same trend as the ultrasonic velocities obtained on concretes not subjected to freeze/thaw.

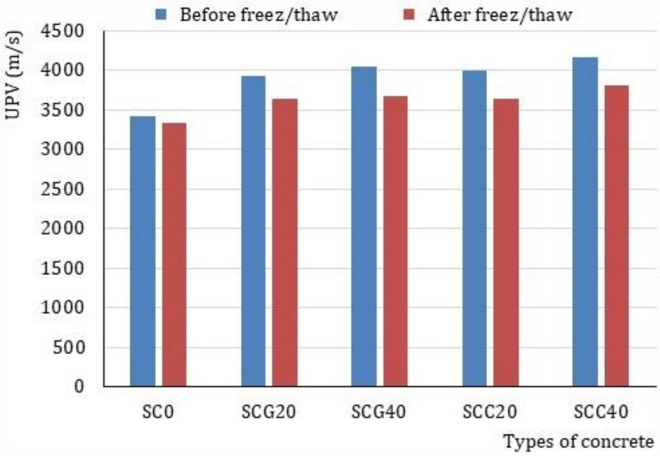

Fig. 23. UPV of concrete before and after freeze/thaw cycles

4.3.5. Modulus of Elasticity

The mixes based on recycled sand before exposure to the freeze/thaw cycle had higher modulus of elasticity than the control concrete (Fig. 24). Further, the same behaviour was observed for concrete exposed to 300 cycles of freezing/thawing. The modulus of elasticity of SCG increases with the increase of the GS rate to reach a value of 35.236 GPa at a rate of 40%, as these results are consistent with the results of a recent study conducted by Amani et al. [51]. In addition, it has shown evident that concretes based on recycled clinker sand give the highest modulus of elasticity before and after freeze-thaw cycles with maximum values obtained at a rate of 40%.

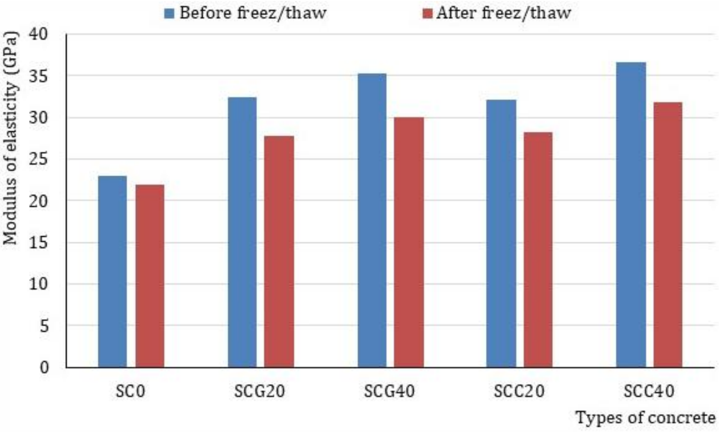

Fig. 24. Modulus of elasticity of concretes before and after freeze-thaw cycles

4.4. Chloride Penetration and Ph of Concretes Exposed to Chloride Attack

The partial replacement of ordinary sand by recycled sand (Fig. 25) results in a reduction in the percentage of chloride ion penetration compared with the reference concrete, whatever the type of sand, and increases with the rate of substitution. Besides, the angularity and roughness of granite sand particles improve the microstructure [52] and develop tortuous capillary paths in the concrete, which could be a cause of preventing chloride ion penetration [48].

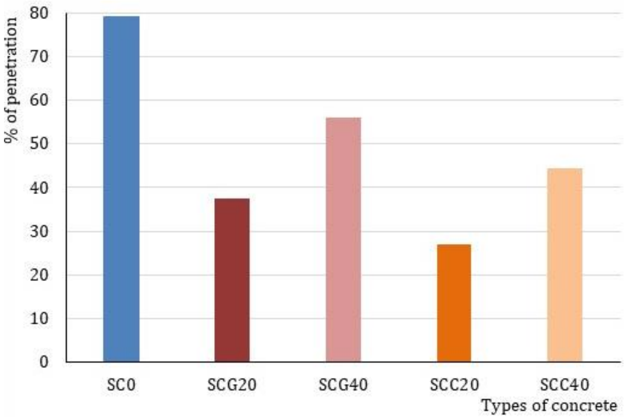

Fig. 25. Percentage of chloride penetration

Concretes containing recycled clinker sand are denser and consolidate the cement matrix better than GS-based concretes (Fig. 26), the fact of which explains the lower penetration percentages in CS-based concretes compared with GS-based concretes.

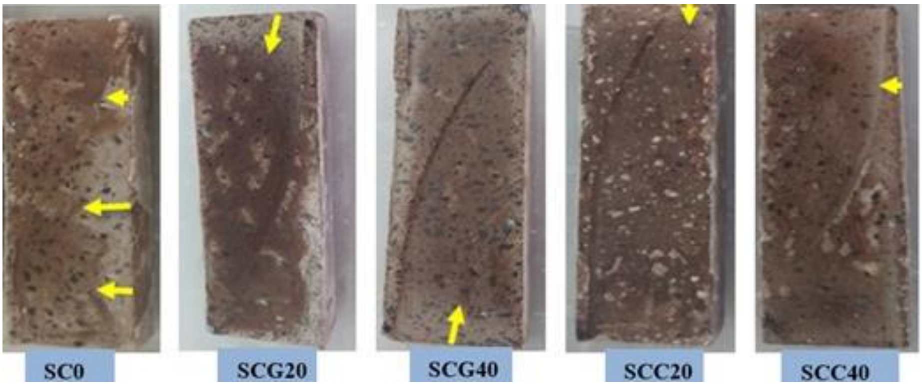

Fig. 26. The split face of the concrete specimen exposes the depth of chloride penetration

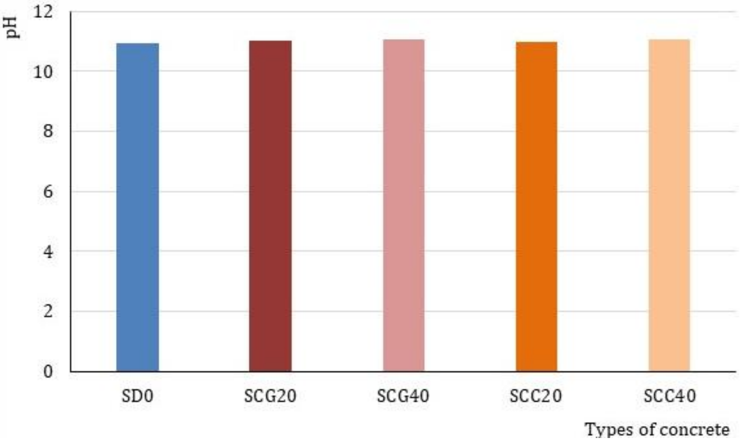

Fig. 27. The concretes' pH exposed to chloride attack

The introduction of recycled sand in place of ordinary sand in the sand concrete (Fig. 27) leads to a slight increase in pH; however, it remains insignificant. Besides, the variation in pH is of the order of 1.35% for the 40% CS concrete, which shows the maximum value (11.08) in comparison with the reference concrete. Subsequent to which, this result can be explained by the presence of a large quantity of CaO in the CS, which strongly reacts in contact with water and forms calcium hydroxide $Ca(OH)_2$, which will dissolve, releasing OH- ions, which will fix the pH of the solution [31]. As a result, this value remains within the range (9 and 13) for non-carbonated concrete.

4.5. Mass variations of concrete exposed to chemical attack (4% HCL and 4% CH_3COOH)

Figure 28 shows that the mass losses of the control concrete are lower than those of the concretes containing recycled sands from waste granite and recycled clinker. Indeed, during the first four weeks of immersion in hydrochloric acid solution, it is observed that the mass loss curves of both SCG40 and SCC40 concretes are increasing and relatively diverging. At the end of this timeframe, they illustrate a loss around 0.93%. This observation is also applicable to the other two concretes, SCG20 and SCC20; however, the mass losses are more significant. The maximum value reached by SCG20 is 2.64%. In contrast, that shown by SCC20 is 2.49%.

From the age of 28 days of conservation, the effect of hydrochloric acid is accentuated and mass losses become more significant. In the end, after 120 days, SCG20 concrete suffers the greatest loss of mass. Further, it lost 5.27% of its mass, exceeding the one of the control concretes (2.75%) and the SCC20 (4.5%). Likewise, it should alike be noted that SCG40 and SCC40 concretes are more resistant to attack by this acid than those incorporating 20% recycled sand. In fact, they lose 4.01% and 3.04% of their mass after 120 days of immersion. Further, this latter value is the closest to that of the control, so this concrete performs best in the series of concretes based on recycled sand.

The recorded rate of attack depends on the composition and permeability of the concrete studied, the mobility of the chloride ions and also the solubility of the salt resulting from the reactions developed within the samples Eq. (2) [54]:

$$Ca(OH)_2 + 2HCl \rightarrow \ CaCl_2 \ + \ 2H_2O \tag{2}$$

In fact, the incorporation of increasing rates of recycled clinker sand and granite waste did not have a positive impact on the chemical resistance of the reference concrete to attack by hydrochloric acid. However, the mass losses of waste granite sand-based concretes are higher than those obtained by concretes containing recycled clinker sand. Besides, this is because the fine particles of the recycled clinker sand are relatively reactive which generates a weak pozzolanic effect and the hydrates thus formed filled some capillary interstices between the grains [53].

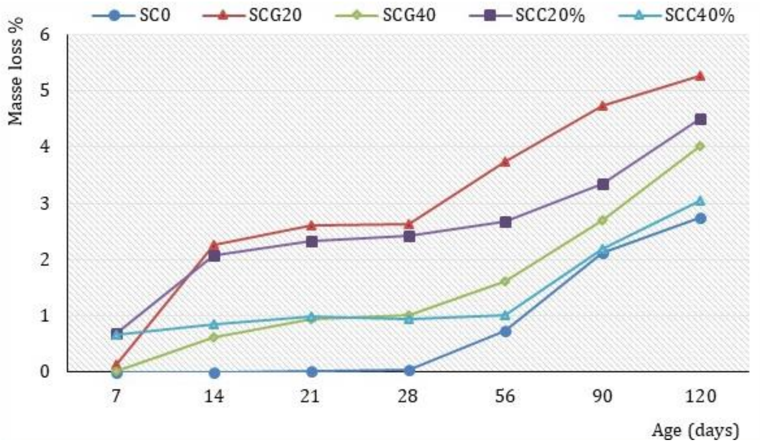

Fig. 28. Mass loss of concrete as a function of immersion period in 4% HCL

Figure 29 shows the mass loss results for concrete immersed in a 4% acetic acid solution. Keeping the concrete samples for four months in the 4% CH_3COOH chemical solution resulted in continuous mass losses over time that diverged in a dissimilar way from the value obtained by the control concrete. Besides, the SCG20, SCG40 and SCC20 concretes underwent mass losses almost similar to those of the control during the 90-day period, after which the trend changed and their degradations became closer and more significant. Moreover, the acquired losses were 5.14, 5 and 4.7% respectively, compared with 4.03% for the reference composition. Besides, the mass loss of SCC40 evolves irregularly, and is visibly greater than that of the control during the period of exposure to acetic acid attack, from 28 to 120 days.

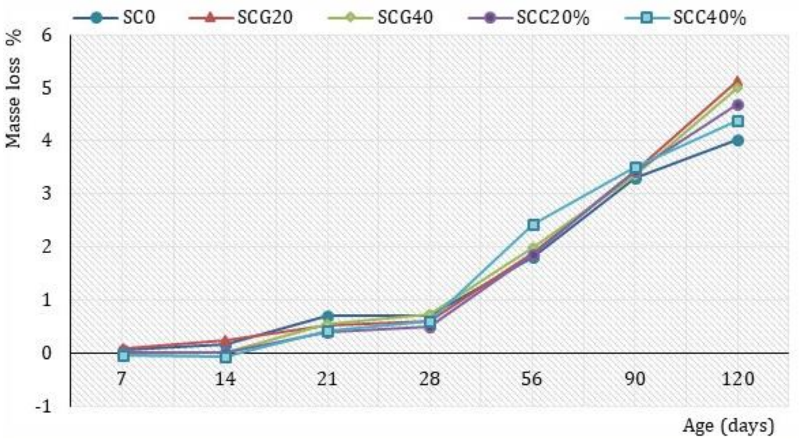

Fig. 29. Mass loss of concrete as a function of immersion period in 4% CH_3COOH

evertheless, in the long term, it can be described as the best-performing concrete in the recycled sand series, as its mass loss is the lowest at 4.37%. In virtue of which, these recorded mass losses can be explained by the fact that acetic acid in contact with the concrete samples can react with the different hydrated and anhydrous compounds in the cement paste (calcium hydroxide, C-S-H, hydrated aluminates, C3S, C2S) in three reactions Eq. (3), Eq. (4) and Eq. (5) [54].

$$2CH_3COOH + Ca(OH)_2 \rightarrow Ca(CH_3COOH)_2 + 2H_2O \tag{3}$$

$$6CH_3COOH + 3CaO.2SiO_2.3H_2O \rightarrow 3Ca(CH_3COO)_2 + 2SiO_2.aq + nH_2O \tag{4}$$

$$6CH_3COOH + 3CaO.Al_2O_3.6H_2O \rightarrow 3Ca(CH_3COO)_2 + Al_2O_3.aq + nH_2O \tag{5}$$

Similarly, it should be noted that the resistance to attack by acetic acid of concretes containing recycled clinker sand is better than that of concretes based on granite sand. Further, the continued presence of fine reactive particles in the recycled clinker sand improves the internal microstructure of the cement matrix, which blocks the mobility of the acid ions to interact with the cement compounds.

4.6. XRD Analyses

In fact, the XRD analysis was carried out on selected concrete samples as shown in Figure 30 to obtain comparative intensities of compounds produced in sandy concrete samples. In this respect, measurements were taken between the intensity and 02 theta values of concrete samples for the peaks if calcite ($CaCO_3$), quartz (SiO_2), Portlandite ($CaOH_2$) and calcium silicate (Ca_2SiO_4). The graph illustrates the presence of quartz and calcite with peaks of maximum intensity for the SCC40 mixture compared with the other mixtures. Further, slightly higher peaks of quartz and calcite were observed for the SCG20 and SCG40 mixtures compared to the control. Likewise, quartz and calcite act as inert fillers in the concrete matrix, resulting in a dense microstructure [55]. Therefore, the presence of Portlandite in optimum amount reduces the pores and alike gives the strength increment [56].

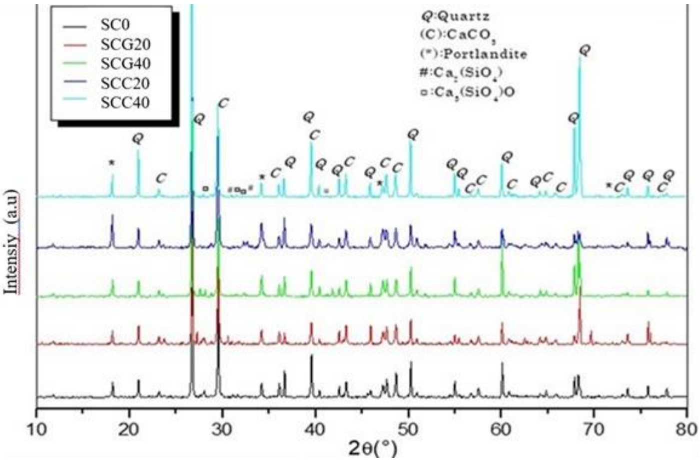

Fig. 30. XRD analysis of concrete

5. Conclusions

Granite and clinker are waste by-products that are harmful to the environment. However, given the large resources of recycled granite and clinker, it appears to be both economically and environmentally useful to use these wastes in concrete production. In this study, the effects of recycled granite and clinker waste sands on the mechanical, durability and microstructural properties of concrete were examined. The main conclusions drawn from this study are:

- The partial replacement of ordinary sand by recycled sand from granite waste and recycled clinker in the formulation of sand concrete makes the latter heavier, more workable and contains more occluded air.
- The partial substitution of dune sand by recycled sand leads to an improvement in compressive strength as a function of the increase in the substitution rate and age. However, concretes containing recycled clinker sand are more resistant in compression compared with granite waste sand.
- The behavior in flexural tension is the same as in compression, with maximum strengths given by concrete containing 40% recycled clinker at ages 7, 28 and 90 days.
- The introduction of recycled sand as a partial replacement for ordinary sand in the formulation of a sand concrete increases the surface hardness and homogeneity of the reference concrete as the substitution rate increases. Moreover, ultrasonic speeds and compressive strengths obtained by sclerometer in concretes based on recycled clinker sand have shown to be higher than in concretes based on granite waste sand.
- The shrinkage of concrete containing recycled sand is greater than that of reference concrete, but recycled aggregates have a positive effect on the swelling of sand concrete, and the lowest values are given by concrete containing 40% recycled sand from granite waste.
- The absorption by immersion decreases as the replacement rate increases, and concretes containing recycled clinker sand give the lowest values.
- The replacement of ordinary sand with 40% recycled sand from granite waste and recycled clinker reduces the porosity accessible to water and makes the matrix more compact.

- The best capillary absorption and sportivity are recorded in concrete made with 20% recycled clinker sand.
- The behavior of the concretes after freeze-thaw cycling showed a beneficial effect on shrinkage and weight loss. Besides, a slight reduction in ultrasonic speed and modulus of elasticity compared with the results obtained on concretes not subjected to freeze/thaw and the best values are given by concrete based on 40% recycled clinker sand.
- The concrete containing recycled sand is more resistant to chloride attack than reference concrete, and concrete made from recycled clinker sand is more resistant to chloride attack than concrete made from granite waste sand.
- The reference concrete is the most resistant in a hydrochloric acid environment compared with the recycled sand-based concrete. Further, the SCC40 and SCG40 concretes are the most resistant in comparison with the SCC20 and SCG20 concretes respectively, with a maximum loss of 5.27% at 120 days recorded in the SCG40 concrete (insignificant value). However, the behavior of the different concretes with respect to acetic acid is very similar, and SCG40 concrete has shown to be the least resistant, with a loss of 5.14% at 120 days. Generally speaking, consequently, the partial substitution of ordinary sand by recycled sand has no significant influence on the resistance of these concretes in hydrochloric and acetic acid environments.
- The microstructural study by X-ray diffraction (XRD) shows an improvement in the microstructure, more than ever in the concrete based on 40% recycled clinker sand.
- A good correlation between the various parameters studied was shown by this study.
- In the light of this study, we can say that the partial replacement of ordinary sand by recycled sand from granite waste and recycled clinker has shown to be beneficial, acceptable and feasible.
- Long-term durability studies and microstructure investigations (SEM and FTIR) for the sand concrete studied in the present research could be conducted in the future. A detailed survey may also be carried out later to assess the impact of waste granite and recycled clinker on the performance of the sand concrete as a partial substitute in cement. Additionally, this survey can explore the performance of other types of concrete.

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