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Research Article

Valorization of plastic wastes (PVC) in sand concretes: Experimental approach and durability analysis

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Abstract

Recent research highlights the use of eco-friendly waste materials, such as plastic, to improve concrete performance and sustainability. Similarly, sand concrete is being enhanced through waste reuse to increase its durability and competitiveness. For confirmation purposes, this study was conducted to investigate the recycling of Polyvinyl Chloride (PVC) plastic wastes, originating from sawing and cutting PVC profiles in carpentry workshops, in the form of fines. The aim was to partially replace limestone fines in the composition of sand concrete at substitution rates of 3%, 6%, 9%, and 12%. Likewise, the development of the properties of such concretes was studied in their fresh state (density, workability) and hardened state (compressive strength and flexural tensile strength, sclerometer test, ultrasonic pulse velocity). As for durability, it was investigated by testing water absorption through immersion and capillary action, water-accessible porosity, and behavior in aggressive environments (H_2SO_4, HCL). In consequence, the results obtained were compared with control samples with a 0% substitution rate. The results have clearly demonstrated that partial substitution led to a significant change in the properties of fresh and hardened concrete. In particular, replacing 6% of fine limestone with recycled plastic waste gave satisfactory results.

1. Introduction

In reality, the world is experiencing economic growth in the production of various materials used in our daily lives, as plastic, particularly polyvinyl chloride (PVC), is the best example thereof, as it is widely used at present in various fields, mainly in the construction sector, such as pipes, windows, doors, and flooring. In addition, global polyvinyl chloride (PVC) production has increased significantly, rising from approximately 3 million tons in 1965 to over 20 million tons annually. This rapid growth contributes to the accumulation of plastic waste, highlighting the need for sustainable recycling solutions [1]. In 2017, its production reached 49 million tons, mainly used in construction, furniture and electronics [2]. Nonetheless, the production and use of PVC in various fields result in the generation of considerable amounts of waste, exceeding 25 million tons per year according to statistics. In Algeria, the National Waste Agency recorded in 2019 approximately 15.31% of plastic waste out of all household and similar waste, equivalent to 2.1 million tons. However, this waste includes polyethylene terephthalate (PET), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC) [3]. Above all, it is well known that this type of plastic is not easily biodegradable, which represents a major challenge for all countries in terms of waste disposal [4]. Basically, this issue has paved the way for research aimed at finding environmentally friendly alternatives to traditional waste disposal methods (such as incineration and landfill),

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particularly recycling in construction materials. In addition, this is all the more important given the irrational consumption of certain raw materials used in construction and concrete, such as sand, cement, and grave.

In fact, a study conducted by Harshit Sangtani et al. [5] examined the replacement of ordinary sand with plastic waste sand (PVC) at varying rates. The results demonstrated a positive impact on the compressive strength of concrete with an optimal replacement rate of 10% at 7, 14, 21, and 28 days; Nevertheless, the strength decreases due to the increase in PVC waste without significantly affecting the workability of fresh concrete. In another study conducted by Kou et al. [1] on various concrete mixtures, where river sand was partially replaced by plastic pipe waste aggregates (PVC) at different rates ranging from 5 to 45%. The study concluded that replacing the waste had a positive impact on certain properties (density and ductility) on the one hand and a negative impact on the workability, compressive strength and tensile strength of concrete, on the other. Concerning the study by Akila et al. [6], it focused on the strength required when replacing waste from plastic water containers and PVC. Moreover, five substitution rates were used: 5%, 10%, 15%, 20% and 25% replacement of sand. The results demonstrated that replacing sand with plastic waste as fine aggregate increases the compressive strength of concrete, but not to the extent where it can endure heavy loads compared to ordinary concrete. Furthermore, the replacement process resulted in a reduction in density. Youcef Ghernouti et al. [7] partially replaced the fine aggregates in concrete with fine aggregates from recycled plastic bags resulting from waste shredding at replacement rates of 10%, 20%, 30% and 40%. Thus, the results demonstrated a positive effect on the workability of fresh concrete, which increases with the waste substitution rate. However, the effect was negative on compressive and tensile strength in the hardened state. Consequently, this resulted in a reduction in strength and a decrease in the speed of sound propagation in the concrete. Sulaiman Mustafa Khazaal et al. [8] studied the possibility of partially replacing sand in concrete with plastic waste, such as Polyvinyl Chloride (PVC) and Polypropylene (PP). Tests were conducted through replacing 10%, 15%, 30%, 45% and 60% of ordinary sand. The results demonstrated a significant increase in compressive strength after 28 days when using 15% and 30% PVC, compared to the use of PP waste, which showed a decrease in strength. On the other hand, Bhosale Swapnil et al. [9] conducted a study on the partial replacement of fine sand in concrete using plastic waste such as Polyvinyl Chloride (PVC). In this respect, tests were conducted replacing 15%, 25% and 35% of the sand and tested the compressive strength at 7, 14, and 28 days. The incorporation of plastic waste into concrete helped to reduce its weight, with a slight decrease in compressive strength, where an optimal replacement value of 15% was observed, accordingly. Studies conducted by Choi et al. [10] and Marzouk et al. [11] confirmed the possibility of using plastic waste, particularly Polyethylene Terephthalate (PET) bottles, in concrete. Nonetheless, this leads to a decrease in the strength of the concrete, both in compression and tension, when the proportion of plastic waste exceeded 0.5% of the total weight of the concrete mixture. The majority of studies agree on the possibility of reusing various types of plastic waste in construction materials in general, and in concrete in particular. The recycling process is considered one of the best environmental, economic and ecological solutions proposed by many researchers. In another study conducted by da Silva A. M. et al. [12] on the effect of using plastic waste as a substitute for sand in mortar, the tested proportions ranged from 5%, 10% and 15% of the volume compared to the control mortar. The results were mixed, showing a reduction in the width of shrinkage cracks, a decrease in the modulus of elasticity and an improvement in impact strength, as well. As a counterpoint, an increase in capillary absorption and water vapour permeability was also observed. Furthermore, a study conducted by Bolat and Erkus in 2016 [2], examined the use of PVC waste in powder and granule form as a partial substitute for aggregates in concrete, at rates of 10%, 20% and 30%. The results demonstrated a decrease in density, capillary absorption and compressive strength, while, abrasion resistance improved with increasing substitution rate. Another study conducted by Boutlikht et al. [13] focused on the use of Polyvinyl Chloride (PVC) waste as a concrete manufacturing material, partially replacing natural sand with PVC fibres and fine sand at volume rates of 5%, 10% and 15%. Consequently, the results demonstrated that PVC reduced the workability of fresh concrete for both types. In addition, the PVC sand decreased compressive strength, unlike PVC fibres, which had a less negative effect.

On the other hand, sand concrete is one of the emerging concrete types due to its countless characteristics that make it an alternative to traditional concrete in certain construction works, such as underground structures, dams, pavements, airports, road infrastructure, and in the rehabilitation of old buildings particularly for injection works [14,15]. Along the same lines, sand concrete is considered one of the materials that attract the interest of researchers in the field of recycling various types of recyclable wastes, mostly those originating from the construction sector, with the aim of developing its properties for its adaptation for widespread use in construction and civil engineering, such as the pouring of foundations, walls, columns, the rehabilitation of old buildings, as well as injection works and repairs. Several studies have been conducted on the recycling of waste in sand concrete. Rihia et al. [16] conducted a study on the possibility of replacing fine natural sand with marble and ceramic wastes sand in a mixture of lightweight sand concrete reinforced with plant fibres. The results demonstrated positive indicators regarding the effect of this substitution on the physical and mechanical properties together with the durability of the concrete. Similarly, wastes can also be used in the form of fibres, as demonstrated by Sayadi et al. [17] in a study on the effect of reusing copper, aluminum and iron waste, transformed into fibres, on the properties of sand concrete, its durability and resistance to chemical attack. With rates of 0.4 to 1.2%, the results proved an improvement in certain characteristics, such as strength and durability, depending on the type and rate of wastes incorporated. In the same context, a few studies have been conducted on the reuse of plastic wastes in sand concrete, but they remain limited. In addition, Guendouz and Boukhelkhal [18] examined the recycling of rubber wastes in sand concrete and their impact on physical (workability, bulk density), mechanical (compressive and flexural strength) and thermal properties, with substitution rates of 10%, 20%, 30% and 40%. Consequently, the results demonstrated a decrease in compressive and tensile strength, along with an improvement in thermal performance. Guendouz et al. [19] studied the incorporation of two types of plastic wastes (Polyethylene Terephthalate (PET) and Low-Density Polyethylene (LDPE) used in the manufacture of bags) in the form of fibres and fine powder in sand concrete as a partial replacement for ordinary sand, at different proportions for each type of waste. Then, the results demonstrated that the use of plastic wastes, mainly at replacement rates of 10% and 20%, reduces the bulk density and air content, thus leading to an increase in compressive and flexural strength, accordingly. Along the same lines, Akinyele and Toriola [20], Davies and Olofinnade [21] conducted a study aimed at producing sand concrete blocks using shredded plastic waste as a replacement for fine aggregate and Polyethylene Terephthalate (PET) wastes at different substitution rates, respectively. They studied the impact of these proportions on compressive strength, tensile strength, density and water absorption. The results demonstrated that it was possible to achieve an increase in strength up to an optimal replacement ratio of 5%. Nevertheless, as the replacement rate increases, the density and water absorption decrease.

Fig. 1. Cutting PVC profiles

Most studies have demonstrated that the use of plastic waste in concrete and mortar is possible, with effects that can be both positive and negative on their properties, depending on the substitution rates and the material replaced, whether cement or, more often, sand. Based on this research, Polyvinyl Chloride (PVC) plastic waste (Fig. 1) were reused as a substitute for limestone fines in sand concrete, at replacement rates of 3%, 6%, 9%, and 12%. Therefore, the aim is to study their impact on the physical and mechanical properties of concrete, together with their durability against chemical attack, as well.

2. Materials Used

2.1. Cement

The cement used in this study is CEM II 42.5, produced at the Hadjar Soud factory in Skikda, Eastern Algeria. It is composed of clinker and two types of additives: blast furnace slag and limestone. Its absolute density is 3.22 g/cm^3 whilst its Blaine specific surface area is 3550 cm^2/g.

2.2. Sand

In this study, the naturally rolled 0/1 mm fraction dune sand (DS) from the Oued Z'hour – Skikda region in Eastern Algeria was used.

2.3. PVC Plastic Wastes (Recycled Fines)

Polyvinyl Chloride (PVC) is a thermoplastic powder composed of carbon, hydrogen, and chlorine, containing approximately 56.7% chlorine. It is produced from Vinyl Chloride Monomer (VCM), an odorless and flammable compound, via suspension, bulk, or emulsion polymerization. In this polymer, the carbon and hydrogen are derived from petroleum, while chlorine is obtained from salt.

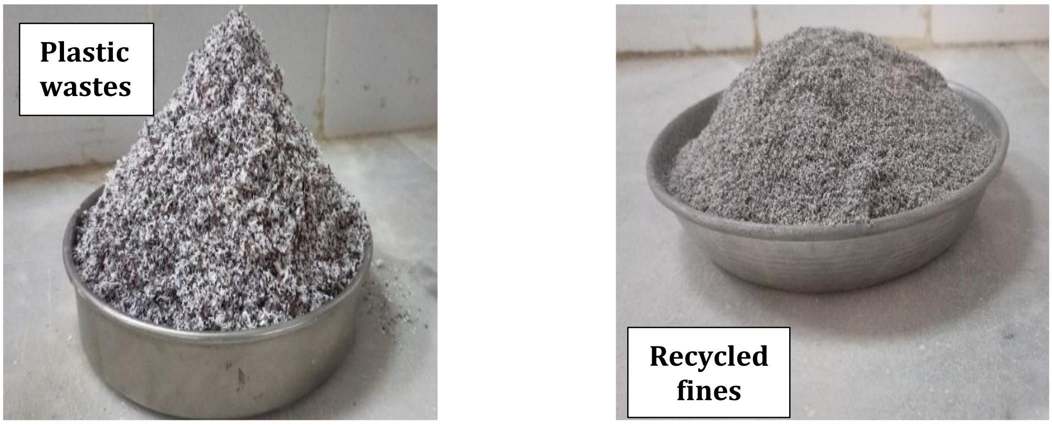

Fig. 2. Recycled fines from plastic waste

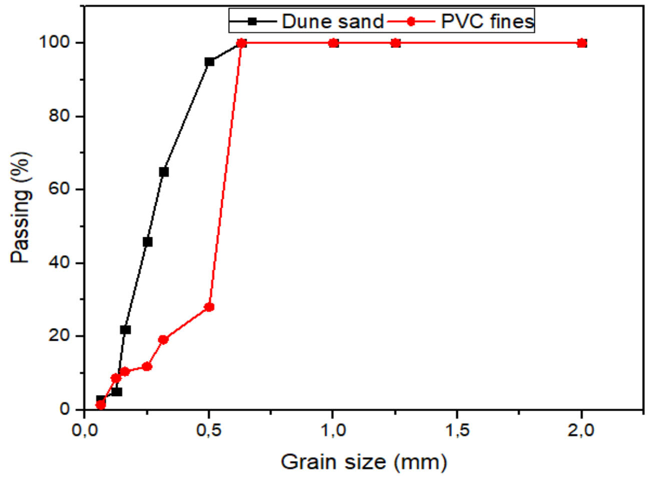

Fig. 3. Particle size distribution curve of dune sand and PVC fines

In this study, PVC wastes were recovered in two stages: the first involved collecting the cuttings from an aluminum joinery workshop (Fig. 2); the second involved obtaining fine particles by sieving the material through a 1 mm sieve, resulting in particles smaller than 1000 µm. An analysis of the particle size distribution of Polyvinyl Chloride (PVC) was carried out (Fig. 3), which has then revealed a percentage of fines (f) equal to 1.4%, with an estimated density of 1.24 g/cm^3.

2.4. Limestone Fines

The fines (F) used in this study consist of finely ground white limestone powder obtained from the Ben Azzouz quarry, east of Skikda. More than 80% of the particles pass through an 80 µm sieve. The limestone fines have an absolute density of 2.741 g/cm^3 and a calcium carbonate ($CaCO_3$) content of 84.60%. Based on the characteristics obtained, it can be stated that:

- The lowest density is observed for PVC fines, which could reduce the overall density of the concrete. Nevertheless, the highest density is that of limestone fines;
- Since the fines content of PVC wastes (1.4%) is lower than that of dune sand; thus, incorporating it could lead to reduced workability, increased segregation, and reduced concrete compactness [22], as well;
- The limestone fines are primarily composed of calcium carbonate ($CaCO_3$) in high proportion, which contributes significantly to the cohesion of the cement matrix, thereby promoting early mechanical strength development [16];
- The dune sand has a fineness modulus below the optimum value, indicating a high proportion of fine and very fine particles, thus requiring an increase in water content to ensure good workability [22];
- The sand equivalent test indicates that the dune sand used is slightly clayey, with acceptable cleanliness. Moreover, it has a continuous particle size distribution (Fig. 3) and is suitable for high-quality concrete where shrinkage is not a major concern.

Table 1. Physical characteristics of materials

Physical characteristics	Bulk density (g/cm^3)	Absolute density (g/cm^3)	Sand equivalent (%)	Absorption (%)	Fineness modulus (%)	Fine content (%)
Dune sand	1.31	2.83	68.02	3.00	1.55	3.00
Limestone fines	1.05	2.74	--	--	--	--
PVC fines	--	1.24	--	--	2.51	1.40

Table 2. Chemical characteristics of materials

Chemical characteristics	CaO (%)	Al_2O_3 (%)	F_2O_3 (%)	SiO_3 (%)	MgO (%)	Na_2O (%)	K_2O (%)	Cl^- (%)	SO_3 (%)	$CaCO_3$ (%)	SO_4 (%)
Cement	66.46	5.40	3.92	21.63	1.29	0.21	0.57	0.01	0.46	--	--
Dune sand	0.80	2.36	1.15	94.09	0.14	0.20	0.58	--	0.01	--	--
Limestone fines	--	--	--	--	--	--	--	0.21	traces	84.60	traces
PVC fines	--	--	--	--	--	--	--	56.70	--	--	--

2.5. Admixture

The superplasticizer (Glenium 26, BASF, Algeria) was used in this study. It is a high-range water reducer, compliant with the NF EN 934-2 standard, ready for use and formulated with modified polycarboxylates. This superplasticizer, which is chlorinated, comes in the form of a light brown liquid with a density of 1.07 ± 0.02.

3. Experimental Program and Tests Performed

3.1. Cement

As part of the experimental program, a concrete made from cement, dune sand, limestone fines, admixture and water were selected as the reference concrete. The limestone fines were then partially replaced by PVC fines. For this purpose, five formulations were developed:

- SC-0%: Sand concrete composed of 0% plastic fines and 100% limestone fines;
- SC-3%: Sand concrete composed of 3% plastic fines and 97% limestone fines;
- SC-6%: Sand concrete composed of 6% plastic fines and 94% limestone fines;
- SC-9%: Sand concrete composed of 9% plastic fines and 91% limestone fines;
- SC-12%: Sand concrete composed of 12% plastic fines and 88% limestone fines.

Essentially, the mixtures were prepared according to the Sablocrete method [23], by keeping certain parameters constant, such as cement dosage, quantity of dune sand, superplasticizer content and water/binder ratio. The studied variables pertained to the substitution rates of limestone fines by plastic fines (PVC). Table 3 illustrates the different compositions of the five formulations.

Table 3. Composition of the mixtures

Formulations	Cement (kg/m^3)	Dune sand (kg/m^3)	Water (l/m^3)	Admixture (l/m^3)	Limestone fines (kg/m^3)	PVC fines (kg/m^3)
SC-0%	321	946	218	2.9	202.42	0
SC-3%	321	946	218	2.9	196.01	2.14
SC-6%	321	946	218	2.9	183.89	4.29
SC-9%	321	946	218	2.9	177.82	6.43
SC-12%	321	946	218	2.9	95.01	8.57

3.2. Tests performed

The following tests were performed on the different formulations:

- The density of the fresh concrete was measured in accordance with the Standard NF EN 12350-6;
- The workability of the concrete was assessed by use of the Abrams cone slump test, in accordance with the Standard NF EN 12350-2;
- The flexural traction strength and compressive strength were measured at 02, 07, 14, 28 and 90 days on 4 × 4 × 16 cm^3 prismatic test specimens, stored in water, in accordance with the Standard NF EN 12390-5;
- The sclerometer test was carried out on 15 x 15 x 15 cm3 test specimens stored in water at 28 days of age in accordance with the Standard NF EN 12504;
- The ultrasonic test was measured on cubic test specimens measuring 15 × 15 × 15 cm^3 after 28 days of curing in water, in accordance with the Standard NF EN 12504-4;
- The water-accessible porosity is measured in accordance with the Standard NF P18-459, on test specimens measuring 4 × 4 × 16 cm^3;
- The capillary absorption was measured on test specimens measuring 4 × 4 × 16 cm^3, in accordance with the Standard NF EN 480-5;
- The absorption by immersion was assessed on cubic test specimens measuring 5 × 5 × 5 cm^3, in accordance with the Standard NBN B 15-215;
- The chemical attack by acids and bases was carried out on 5 × 5 × 5 cm^3 test specimens stored during 28 days in water and then in the chemical solution. Then, weight loss and strength loss were measured according to the age of the test, in accordance with the Standard ASTM C-267-96;
- The chloride permeability was measured on 5 × 5 × 5 cm^3 test specimens stored during 28 days in water, then immersed in a solution containing 5% sodium chloride (NaCl). Afterwards, the samples were cut and then treated with a silver nitrate solution on the cut concrete surface, in accordance with the Standard NT BUILD 492-1.

4. Results and Discussion

4.1. Density

Based on the results shown in Fig. 4, it can be concluded that the use of recycled Polyvinyl Chloride (PVC) plastic wastes as a partial substitute for limestone fines in sand concrete resulted in a decrease in density compared to the control concrete. The minimum density value was observed for the maximum substitution rate of 12%, reaching approximately 2.142 g/cm^3; corresponding to a decrease of 3.86% compared to the reference mixture. Nonetheless, this decrease can be explained by the lower density of PVC fines compared to that of limestone fines. Therefore, these results are in agreement with those obtained by Senhadji et al. [24].

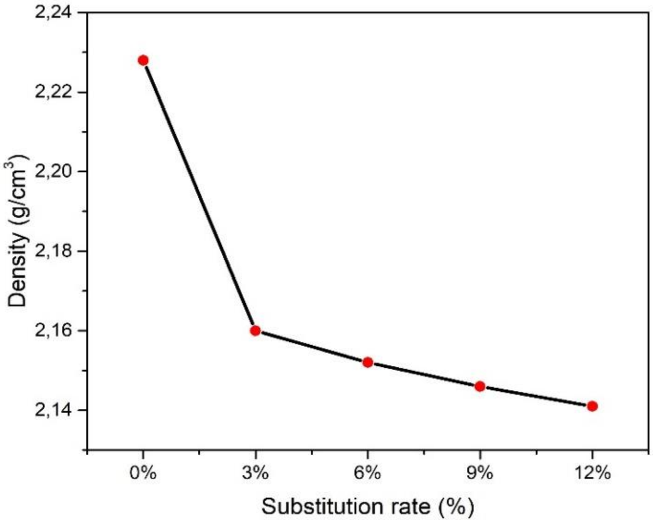

Fig. 4. Variation in density according to the rate of substitutions

4.2. Workability

Fig. 5 demonstrates that increasing the substitution rate of limestone fines with recycled plastic wastes in sand concrete, up to an optimal threshold of 6%, improves workability, with an increase of up to 30% compared to the reference concrete. This improvement is due to the low water absorption of plastic particles [25,26]; Nonetheless, above this threshold, workability gradually decreases, which can be attributed to the angular and irregular shape of the plastic fragments, mainly at higher substitution rates [27,28].

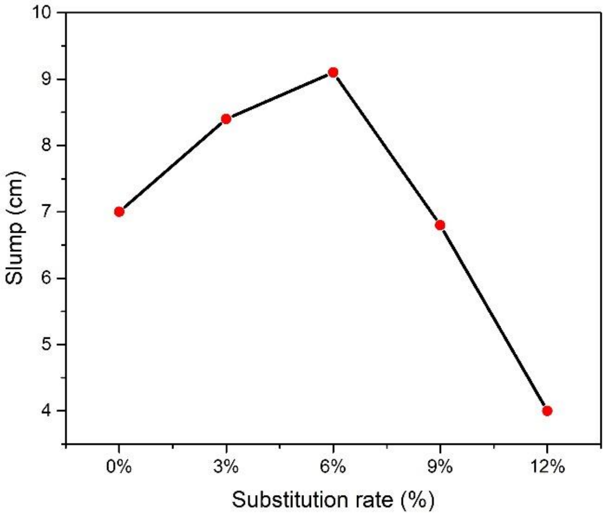

Fig. 5. Variation in workability according to the rate of substitutions

4.3. Compressive Strength

The results of compressive strength tests at 7, 28 and 90 days on sand concrete mixtures incorporating Polyvinyl Chloride (PVC), shown in Fig. 6, clearly demonstrated a decrease in compressive strength with increasing substitution rate of plastic wastes at all ages, compared to the reference concrete. Above and beyond, this decrease is particularly significant for the maximum substitution rate of 12% at 7 days, where a reduction of approximately 55% was recorded. The same downward trend is observed for the other substitution rates, although it is less pronounced, mainly at 3%. This behavior can be attributed to the low adhesion between the surface of the PVC grains and the cement paste. Furthermore, as PVC is a hydrophobic material, this characteristic may limit the penetration of water necessary for cement hydration through the structure of the samples during the curing period [2].

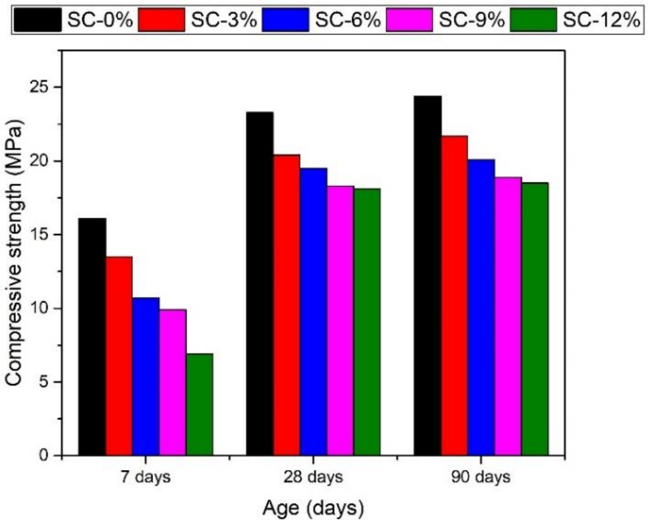

Fig. 6. Influence of the rate of substitutions on compressive strength

The results demonstrated that replacing limestone fines with plastic fines shows a trend of increasing compressive strength in sand concrete over time. Nevertheless, this strength remains lower than that observed for the reference concrete at 7, 28 and 90 days (Fig. 7). Additionally, the obtained experimental observations are consistent with those reported in numerous previous studies [29,30]. Along the same lines, this behavior could be explained by a decrease in the density of the concrete, leading to a potential increase in porosity, as well as the weak cohesion between the plastic particles and the other constituents of the concrete.

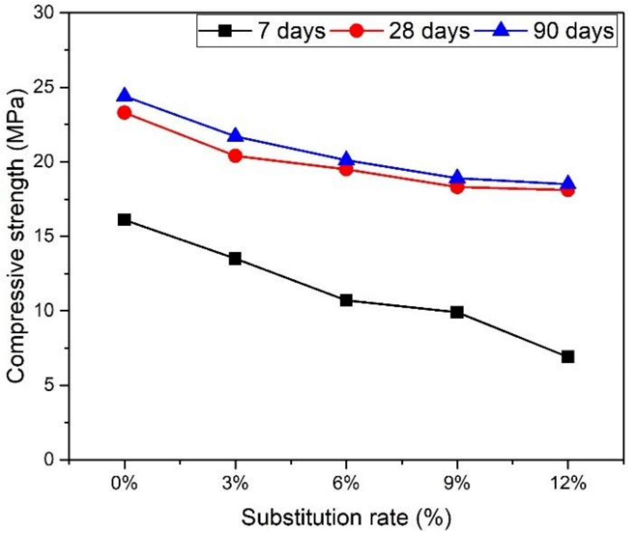

Fig. 7. Evolution of compressive strength according to the age

4.4. Flexural Tensile Strength

As shown in Fig. 8, the behavior of flexural tensile strength generally follows the same trend as compressive behavior, with a decrease in strength as the substitution rate increases across all curing ages. This reduction in strength is attributed to the low adhesion between the Polyvinyl Chloride (PVC) particles and the cement paste, as well as to the accumulation of bleeding water due to the low absorption rate of the plastic waste particles, which led to a weakened bond within the cement matrix [1]. Notably, the SC-3% mixture containing 3% recycled fines illustrated the best flexural strength performance at 7 days compared to the other formulations.

However, the mixture containing 9% plastic fines demonstrated a notable improvement in performance at 28 and 90 days, with tensile strengths of 6.78 MPa and 7.66 MPa, respectively. Moreover, these values are higher than those of other formulations containing plastic wastes, although they remain slightly lower than those of the reference concrete. This suggests that satisfactory tensile strength can be attained with an optimal substitution rate, despite the general trend towards decreased mechanical performance [31]. Indeed, tensile strength tends to increase over time, particularly at 7, 28 and 90 days, as illustrated in Fig. 9 for all formulations. Nonetheless, mixtures containing fines from plastic wastes have lower strengths than the reference concrete. Thus, a substitution rate of 9% can be considered an optimal value for attaining satisfactory strength at the ages of 28 and 90 days.

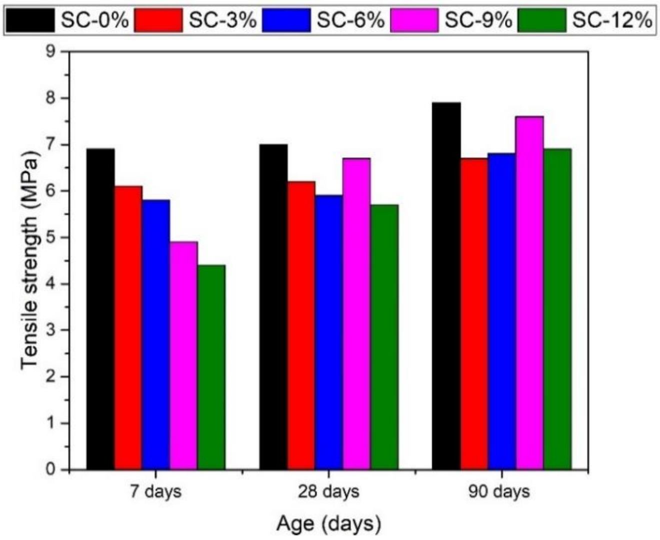

Fig. 8. Influence of the rate of substitutions on flexural tensile strength

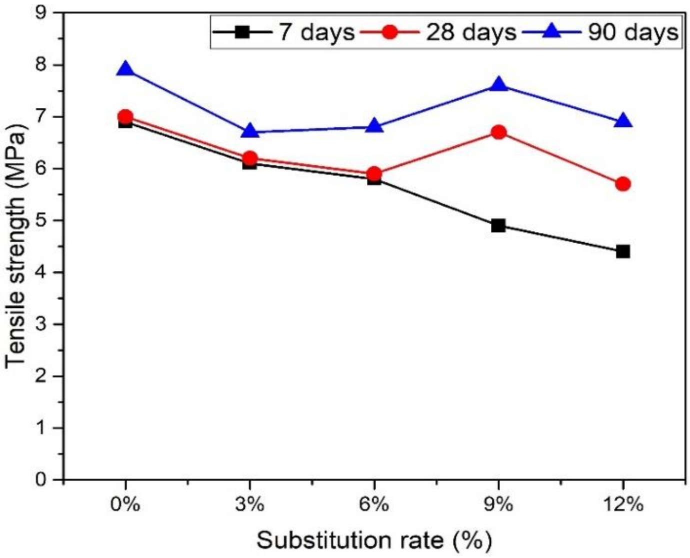

Fig. 9. Evolution of tensile strength in flexion according to the age

4.5. Compressive Strength Obtained by the Sclerometer Test

Based on the results obtained, it can be observed that the sclerometric index slightly increases compared to the control concrete, reaching values of 22 and 23 for substitution rates of 3% and 6%, respectively. Beyond these rates, the addition of recycled plastic fines becomes unfavorable. To better highlight the relationship between mechanical and surface properties, Fig. 10 presents the correlation between compressive strength and the sclerometric index, regardless of the substitution rates. A strong linear relationship is observed (R^2 = 0.9995), indicating that the sclerometric test can be used as a reliable indirect method for estimating compressive strength.

Similar trends are observed for compressive strength, where the maximum value was recorded at a substitution rate of 6%, reaching 16.53 MPa, which represents the best performance among all tested formulations. Consequently, replacing 6% of fine particles with recycled plastic significantly improves the compactness and strength of sand concrete mixture [32].

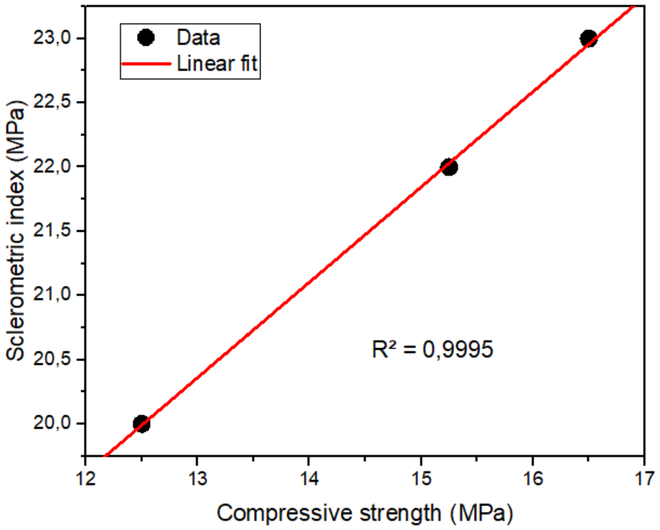

Fig. 10. Correlation between compressive strength and sclerometric index

4.6. Compressive Strength Obtained by The Ultrasonic Testing

Indeed, Fig. 11 demonstrates the ultrasonic wave velocities measured on concrete samples after 28 days of curing. Moreover, the results indicate a gradual decrease in ultrasonic pulse velocity (UPV) as the substitution rate of limestone fines by recycled fines increases. Specifically, this decreases ranges from 3472 m/s for the reference concrete to 3103 m/s for the concrete with a substitution rate of 12%.

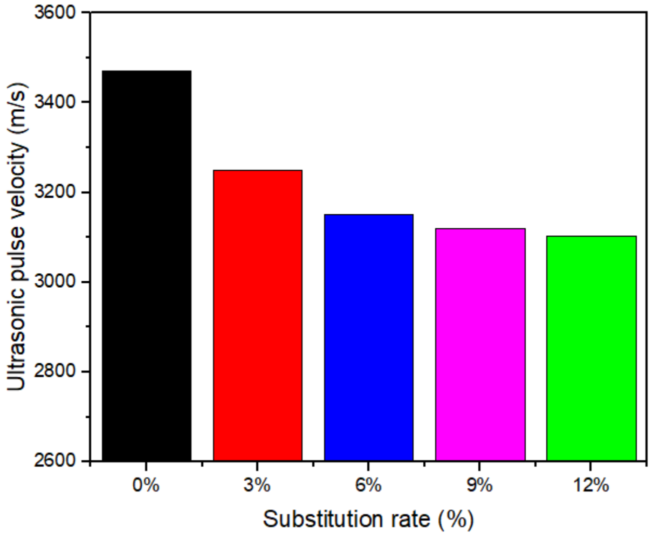

Fig. 11. Influence of substitution rate on propagation velocity

These observations indicate that the introduction of plastic waste fines into concrete reduces its density, which negatively affects the porosity thereof. Actually, the pores generated by these fines weaken the ultrasonic pulse velocity waves. Besides, this can be explained by the fact that these waves are partially reflected and partially transmitted when they pass through the PVC fines, voids and concrete, leading to a decrease in their speed [28]

4.7. Water Absorption by Capillarity

The results presented in Fig. 12 indicate that the capillary water absorption coefficient increases with the incorporation of recycled Polyvinyl Chloride (PVC) fines. This behavior can be attributed to the low adhesion between the matrix elements and the plastic fines, which makes this matrix more porous and therefore more likely to retain water. On the other hand, the low absorption capacity of PVC fines can lead to an increase in the amount of free water in the concrete, thus promoting the formation of interconnected voids following the evaporation of this water, which leads to an increase in the average size of capillary pores [21,16]. The capillary absorption rate decreases over time for all types of concrete, with the highest coefficient recorded for the SC-12% mixture.

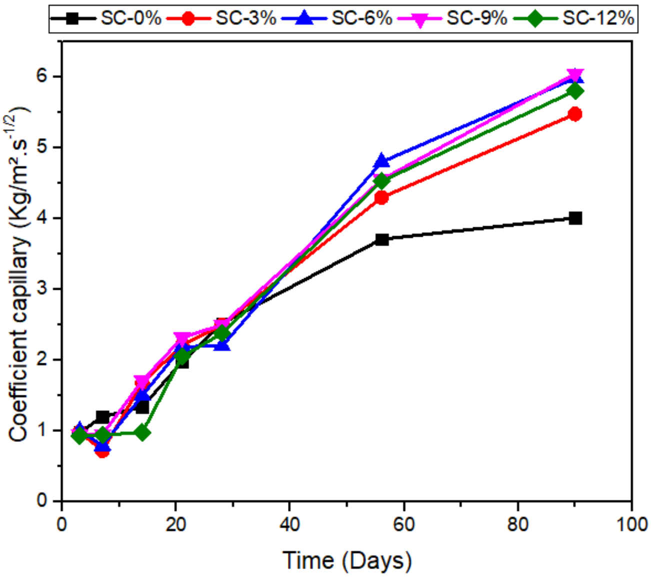

Fig. 12. Water absorption by capillarity vs time

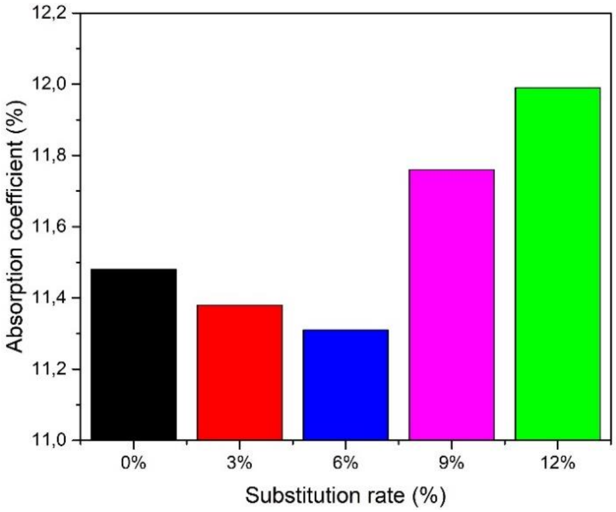

Fig. 13. Variation in the water absorption coefficient by immersion according to the rate of substitution

4.8. Water Absorption by Immersion

The results presented in Fig. 13 indicate that replacing limestone fines with recycled plastic fines leads to a decrease in absorption for substitution rates of 3% and 6%. Above this threshold, the effect is reversed and the absorption rate increases with the increase of substitution rate, attaining a maximum value at 12%. This behavior can be explained by the increase in specific surface area caused by the addition of Polyvinyl Chloride (PVC) relative to Portland cement. Consequently, the PVC particles partially cover the surfaces of fine aggregates, leaving some areas uncoated [33]. Moreover, the 6% substitution rate, which provided good concrete surface strength, indicates that this mixture is more homogeneous and of better quality, thus reducing the absorption process, accordingly [32,33].

4.9. Chemical Attacks

4.9.1 Chemical Attacks by A 4% Sulphuric Acid (H_2SO_4) Solution

Figure 15 illustrates the evolution of mass gain in the concretes studied when exposed to a Sulphuric Acid solution. It is evident that during the early stages (3 and 7 days), mass gain remains low for all formulations, particularly those incorporating Polyvinyl Chloride (PVC) fines. At intermediate ages (14, 21 and 28 days), the differences between the mixtures become more pronounced; the mixture containing 12% PVC shows almost constant mass stability, unlike the other formulations, which show more marked variations.

Fig. 14. Measurement of mass loss

Nevertheless, between 56 and 90 days, a notable increase in mass gain is observed, reaching a maximum value of 6.13% for the formulation with a substitution rate of 9%. In general, this mass gain can be attributed to the absorption of water or acid solution into the micro-voids between the polyvinyl particles and the cement matrix, as well as at the edges of the samples, which have shown not to be completely protected. This penetration promotes specific chemical reactions, in particular:

- The reaction Eq (1) between sulphuric acid and calcium hydroxide forming gypsum:

$$Ca(OH)_2 + H_2SO_4 \rightarrow CaSO_4.2H_2O \tag{1}$$

- Then the reaction Eq (2) between calcium sulphate and hydrated calcium aluminates, producing ettringite:

$$3CaSO_4 + 3CaO.Al_2O_3.6H_2O + 26H_2O \rightarrow 3CaO.\ Al_2O_3.\ 3CaSO_4.32H_2O \tag{2}$$

Indeed, the deposition of calcium sulphate or other salts in the fine pores leads to an increase in the total mass of samples. Moreover, the polyvinyl is known for its resistance to acidic environments, in respect such as wastewaters that can generate sulphuric acid; therefore, particles from polyvinyl wastes act as a protective barrier, limiting mass loss and concrete degradation over time [34,35,36].

This interpretation is consistent with the findings of Senhadji et al. [37], which illustrated that PVC aggregates have a relatively impermeable structure and a partial acid retention capacity in their pores. This reduces the penetration of acid into the cement matrix and limits surface reactions in a controlled manner. This results in the precipitation of products such as gypsum and ettringite inside the pores, rather than the dissolution of components, which contributes to an increase in mass and improved resistance of the concrete to long-term acid attack.

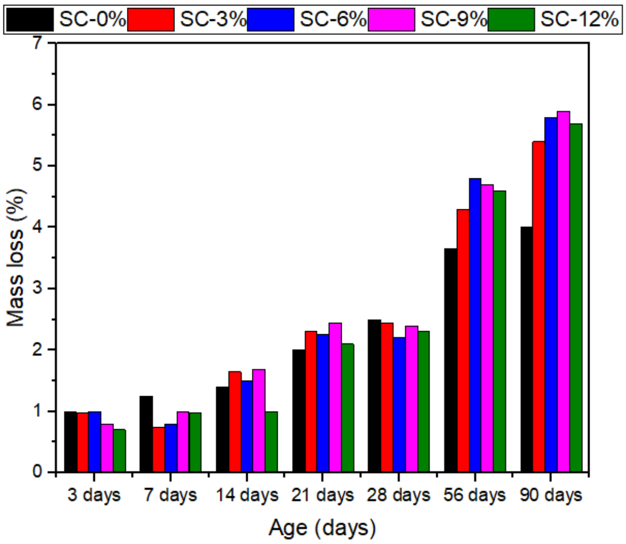

Fig. 15. Variation in mass loss of dune sand concrete as a function of immersion time in 4% H_2SO_4

4.9.2 Attacks by A 4% Hydrochloric Acid (Hcl) Solution

Fig. 16 illustrates the results relating to the mass loss of concrete subjected to a hydrochloric acid solution. It can be noticed that all formulations show a decrease in mass, a phenomenon attributable to the chemical reaction of hydrochloric acid with portlandite $Ca(OH)_2$ and lime $CaCO_3$ resulting from cement hydration. Further, these reactions produce calcium chloride ($CaCl_2$), a highly soluble compound that is particularly harmful to the mechanical and durability properties of concrete [17]. Hence, these processes can be represented by the equations Eq (2) and Eq (3) below:

$$2HCl + Ca(OH)_2 \rightarrow CaCl_2 + 2H_2O \tag{3}$$

$$2HCl + CaCO_3 \rightarrow CaCl_2 + CO_2 + H_2O \tag{4}$$

The reference concrete records the greatest loss of mass up to 21 days. From 3 to 21 days, losses varied according to the substitution rate with polyvinyl wastes. At 28 days, the differences become more pronounced: the minimum value is observed for sand concrete containing 6% recycled plastic fines, whilst the maximum loss is recorded for concrete containing 12%, accordingly.

In effect, a substitution rate of 6% can be considered optimal for increasing resistance to chemical attack by hydrochloric acid. This improvement can be explained by a mechanism similar to that observed with sulphuric acid, where the polyvinyl particles retain some of the acid ions, thereby reducing the intensity of the attack and limiting the degradation of the cement matrix [37,34].

The SC-6% mixture illustrates good performance in immersion absorption and surface resistance tests. Further, the incorporation of this percentage reduces the absorption coefficient compared to other formulations, thanks to improved compactness and homogeneity of the matrix, as well as an increase in surface resistance [32]. Therefore, these improvements result in better long-term properties and increased resistance of concrete to chemical attack by hydrochloric acid [16].

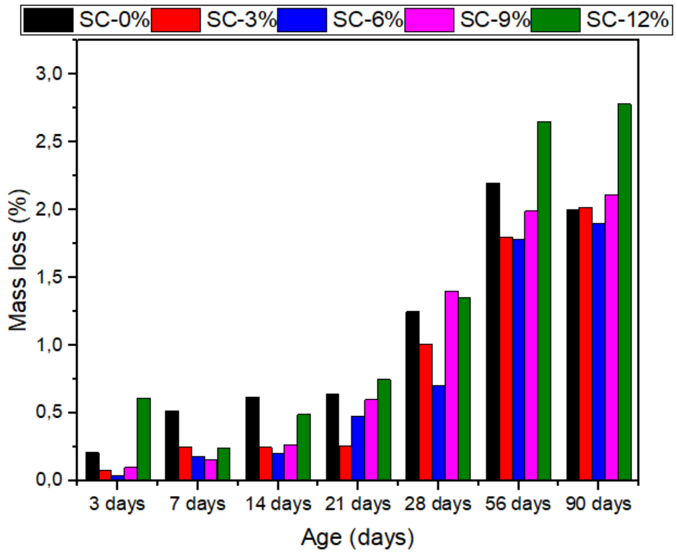

Fig. 16. Variation in mass loss of sand concrete according to the immersion time in 4% HCl

4.9.3 Chloride Penetration

According to the results obtained and presented in Fig. 17, the lowest chloride ion penetration depth was recorded for the SC-0% reference concrete. This finding indicates that this mixture is more homogeneous and compact, due to the filling effect exerted by the particles (cement, limestone fines and sand), which reduces the size of the internal pores of the concrete, as well as its SiO_2 and CaO contents, giving it better resistance in aggressive environments [16,22,38]. On the other hand, the incorporation of fines from plastic waste leads to an increase in the penetration depth of chloride ions. The maximum value was observed for a substitution rate of 3%, reaching approximately 31 mm, corresponding to a considerable increase of 416% compared to the reference concrete. Beyond this percentage, the increase in the content of recycled polyvinyl chloride fines leads to a decrease in the penetration depth, which nevertheless remains higher than that measured for the reference mixture.

This behavior reflects the concrete's lower resistance to chloride ion penetration. Further, these observations differ from those reported by Kou et al. [1] and Senhadji et al. [24]. In fact, the presence of polyvinyl in concrete could promote the formation of voids due to the low adhesion between the plastic particles and the cement matrix, a phenomenon that is particularly pronounced at low substitution rates [39].

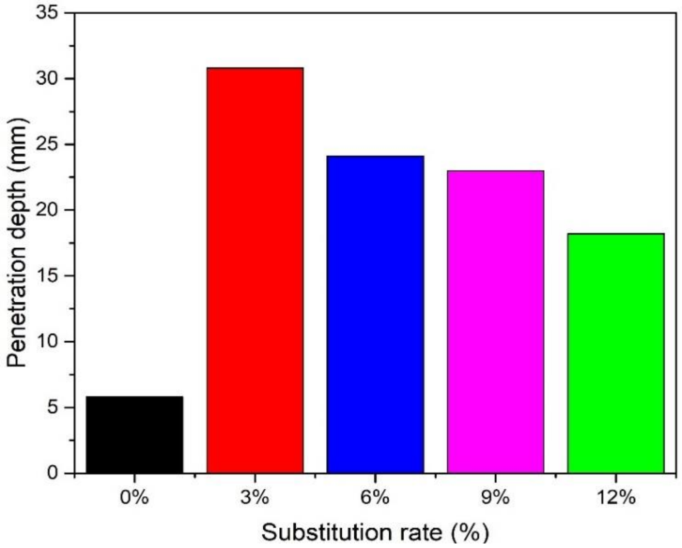

Fig. 17. Variation in chloride penetration depth according to the substitution rate

4.9.4 Water-Accessible Porosity

In general, the partial replacement of limestone fines with recycled polyvinyl fines (Fig. 18) leads to a decrease in water-accessible porosity, regardless of the rate of substitution, compared to the SC-0% reference mixture. The minimum value recorded in this test was observed for concrete with a substitution rate of 6%, with a water-accessible porosity of 21.6%.

This behavior can be explained by the fact that plastic is known to be hydrophobic, representing a low affinity for water. Further, the presence of plastic particles in the concrete composition thus reduces the voids accessible to water, while also limiting the amount of water retained between the concrete constituents [40,32,20]. Subsequently, polyvinyl fines occupy the spaces in the reference concrete matrix that were initially accessible to water, with a content of 6% considered optimal for achieving minimal porosity.

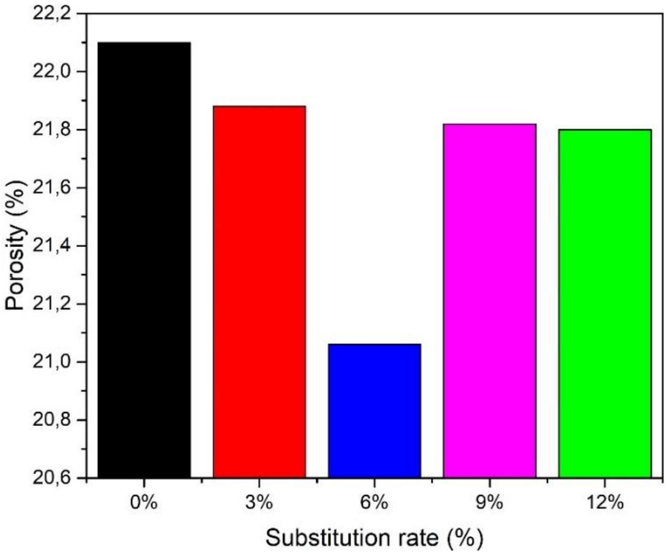

Fig. 18. Variation in water-accessible porosity according to the rate of substitution

5. Conclusions

In light of the results obtained in this experimental study, several important conclusions can be drawn, as follows:

- Incorporating the recycled polyvinyl wastes as a partial substitute for limestone fines reduced the density of the sand concrete, making it lighter;
- The best workability was attained with the mixture containing 6% recycled polyvinyl fines;
- The use of recycled polyvinyl waste as a partial replacement for limestone fines in sand concrete resulted in a decrease in compressive and tensile strengths, while maintaining acceptable values depending on the substitution rate;
- The best flexural tensile performance was observed for the SC-9% mixture, containing 9% recycled polyvinyl fines, compared to the other formulations, at 28 and 90 days;
- The maximum surface hardness was obtained for a 6% replacement of limestone fines with recycled polyvinyl fines;
- The ultrasonic pulse velocity decreases with increasing levels of the recycled PVC fines, indicating reduced homogeneity of the sand concrete;
- The incorporation of recycled PVC fines leads to an increase in the rate of water absorption by capillarity, with the mixture containing a 12% substitution rate recording the maximum absorption value;
- The 6% PVC fines content is considered the optimal percentage for achieving a lower immersion absorption rate than the other mixtures;
- The incorporation of polyvinyl fines improved durability and increased the mass of the concrete when exposed to sulphuric acid (H_2SO_4), with no loss of mass observed for all substitution rates;

- A substitution rate of 6% is optimal for limiting the penetration of hydrochloric acid (HCl) and, consequently, reducing the mass loss of sand concrete;
- Recycled polyvinyl plastic fines did not reduce chloride ion penetration, regardless of the substitution percentage;
- The incorporation of PVC fines, for all substitution rates, leads to a decrease in water-accessible porosity, with a minimum observed for a substitution rate of 6%.

These findings suggest that sand concrete incorporating PVC waste can be effectively used in non-structural applications such as paving blocks, masonry units and lightweight construction elements.

In conclusion, it can be said that recycling polyvinyl waste as a substitute for limestone fines has an overall positive impact, depending on the substitution rates and the targeted properties. This encourages further research and experimentation to optimize results and explore other characteristics.

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