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Assessment of the PVC Waste Addition Effect on the Concrete Mechanical Performance

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ABSTRACT

The purpose of this study is to investigate the possibility of using the polyvinyl chloride (PVC) wastes as a concrete manufacturing material without pre-treatment. The purpose is also to contribute for restricting environmental pollution and exploitation of natural resources, through the stabilization and the solidification of PVC wastes in concrete. The aim of this experimental study is to evaluate experimentally the fresh and cured properties of PVC concrete based in comparison with ordinary concrete (OC). This study consists in collecting PVC waste, especially the used PVC pipes rejected in nature, and incorporate it into concrete by substitution of sand with different volume ratios (5%, 10% and 15%). In this study, two different shapes (Fiber and Fine) of PVC were considered. According to the test results, the addition of PVC waste in concrete as a partial replacement for natural sand conducts to decrease the workability of fresh concrete. It was noticed that, the concrete with PVC fiber shows a lower workability comparatively with fine PVC concrete. It was also observed that the PVC fiber improves the concrete compressive strength. It increases with increasing the replacement ratio of PVC waste. However, the increase in the ratio of fine PVC leads to a decrease in compressive strength. The better mechanical performance factor (MPF) was obtained for concrete mixes with high PVC fiber and moderate PVC fine ratios. The collected outcomes would contribute to helpful information for recycling PVC waste in concrete mixes.

1. INTRODUCTION

Nowadays, PVC has been considered one of the most used materials in manufacturing products. By considering the lifespan of PVC wastes which is estimated from 30 to 50 years, a considerable increase in the PVC wastes production is expected in the near future [1, 2]. The Algerian Ministry of Environment and Renewable Energy reported that the global cost of recycled waste is more than 38 billion Algerian Dinar annually [3]. Babafemi et al. [4] have presented the amount of plastic waste produced and disposed between 1950 and 2019, as well as the predicted amount by 2050. Statistic studies have shown that, 16% of the produced wastes were recycled by 2017 [5].

There have been several researches interested on the various methods for recovering and converting PVC waste to other products, such as mechanical and thermal recycling processes (steam gasification and pyrolysis which involve high temperature treatment). The gasification method can be carried out by air atmosphere, steam, oxygen, carbon dioxide, or a combination of these gases. Air gasification has advantages of simplicity and low cost compared to oxygen [6-8]. The gasification method is suitable for PVC waste that can not be mechanically recycled, such as mixed or heavily contaminated waste. This method can be expensive and energy-intensive. The mechanical recycling of PVC waste is preferred provided that the plastic waste must be uncontaminated and homogeneous. Up until now, there are no practical methods to recycle efficiently the PVC wastes.

The recovery of the used PVC and their insertion in concrete mixes appears as the suitable solution due to its ecological and economic benefits. The process is simple, it consists of crashing the PVC wastes with different grain sizes. The technical feasibility of this process is investigated based on experimental data and the implementation of practical grain sizes where possible (Fiber and Fine). Many recycled materials were used in concrete to substitute aggregates or cement such as construction, electronic, and agricultural wastes [9-14]. Furthermore, the recovered PVC wastes have been studied in numerous investigations to substitute aggregates for developing sustainable concretes [4, 15-17].

The impact on the resistance and the energy absorption capacity of concrete containing polyethylene terephthalate (PET) were studied by Saxena et al. [18]. In this study, four PET ratios of 5%, 10%, 15% and 20% were considered. They have concluded that the PET addition in mortar entrains a compressive strength loss. Li et al. [19] have studied the possibility of the addition of tire-rubber to self-compacting concrete. Larger, medium and powder rubber particles were adopted using three natural sand replacement ratios of 10%, 20%, and 30%. They have found, on the one hand, a slight decrease in workability due to the addition of tire rubber aggregates and on the other hand, an increase in the air content of fresh concrete. Moreover, the use of rubber aggregates allows achieving a high resistance to chloride ion penetration and low water absorption in self-compacting concrete.

Islam et al. [20] have experimentally investigated the use of PET waste in concrete mixtures. Several natural coarse aggregate replacement ratios ranged from 20% to 50% and three water to cement (W/C) ratios 0.42, 0.48 and 0.57 were adopted. The examined parameters were the workability, the density and the compressive strength. They have deduced that, increasing of both PET replacement and W/C ratios reduce the unit weight and the compressive strength of concrete mixture.

To study the effect of using plastic waste as a partial replacement of fine aggregates, on the fresh characteristics of self-compacting concrete as carried out by Hama et al. [21]. In this study, five plastic ratios content (2.5%, 5%, 7.5%, 10% and 12.5%) and three different sizes of plastic wastes (fine, coarse and mixed) were considered. The authors reveal that the studied sizes and contents of plastic waste can be employed as a fine aggregate. Serifou [22] has experimentally studied the use of crushed glass, tire-cut rubber and hardened cement wastes in concrete. For each wastes type, five replacement ratios in mass of coarse aggregates were examined. The replacement ratios were ranged from 20% to 50%. The author showed that the recycling concrete has a lower compressive strength than the ordinary concrete made by natural crushed aggregates. Moreover, the mechanical strength decreases with increasing the substitution ratio.

As mentioned above, though several researches were conducted on use of PVC waste in concrete mixtures, the gained consequences from literature were evolved. Consequently, there is still necessary to assess the concrete mechanical proprieties based on PVC waste aggregates and to identify the shape and the optimal replacement ratio of PVC aggregates.

The present paper reports the experimental investigation on the effect of natural sand replacement by PVC waste aggregates on concrete properties. In this study, three PVC replacement ratios of 5%, 10% and 15% were considered. For each ratio, two-sizes of crushed PVC wastes were examined (Fiber and Fine). The mechanical properties of different concrete mixtures were analyzed. Furthermore, considering the obtained experimental results, empirical equations that describe the correlation relationship between tensile strength, density, and compressive strength, are developed.

2. EXPERIMENTAL PROGRAM

2.1 Materials

The different materials properties used in the preparation of concrete mixtures were determined in the laboratory according to the pertinent practice code ACI 318-11 [23]. An Algerian manufactured Portland cement (CEM II/A 42.5R) type was used. This one comes from the cement company of Ain El Kebira-Setif (http://www.scaek.dz/Apropos).

This cement has a specific surface area of 385 m^2/kg, an absolute density of 3100 kg/m^3, and an average compressive strength at twenty-eight days of 52.5 MPa, is used for casting the specimens of all concrete mixes. In this study, two coarse aggregates of quarry were obtained from the eastern region of Algeria were used. The first one has a nominal maximum size of 16 mm, while the second one has a 25 mm of size. The used fine aggregate was a dune sand taken from Lioua-Biskra (NE of Algeria). The key aspect of this study is to recycle the PVC wastes where two PVC aggregates shapes were used in concrete mixtures (Fiber and Fine). The PVC waste aggregates were used as replacement of the dune sand in concrete with various volume ratios of 5%, 10% and 15%. The coarse and fine aggregates properties are summarized in Table 1.

Table 1. Properties of coarse and fine aggregates

Properties	Aggregates values	
	Coarse	**Fine (sand)**
Colour	Grey	Yellow
Shape	Angular	Round
Type	Crushed	Uncrushed
Maximum Size (mm)	25	05
Bulk Density (kg/m^3)	2.65	2.60
Apparent Density (kg/m^3)	1.46	1.63
Water Absorption (%)	0.2	1.4
Flakiness Index (%)	27	/
Los Angeles (LA) (%)	70	/
Micro-Deval $_{Water}$ (MDw) (%)	86	/
Fineness Modulus	/	3.2
Sand-Equivalent (SE) (%)	/	62

Prior to the preparation of the mixtures design, physical and mechanical tests were performed on all concrete components, including Water Absorption (WA), Flakiness Index (FI), Sieve Analysis (SA), Los Angeles (LA), Micro-Deval$_{Water}$ (MD_W), Fineness Modulus (FM) and Sand Equivalent (SE). The aforementioned tests were carried out according to the standard NF EN 933-1-2012 [24]. All physical and mechanical characterizations, specimens' preparations, compressive and tensile tests were carried out in the construction material laboratory (UFAS-1). The Tables 2-4 present the sieve analysis results of coarse and fine aggregates, respectively.

In this study, the fine PVC was used as sand replacement in concrete (Figure 1). The PVC was directly collected from PVC pipes waste from the production factory of K-Plast group (http://www.groupekplast.com).

Figure 1. PVC pipe waste

Figure 2. Crushed PVC waste: (a) Fine PVC and (b) Fiber PVC

The proprieties of the crushed PVC pipes used in concrete mixtures were presented in Table 5. Figure 2 shows the shape of the PVC waste after crushing. Therefore, the results of the sieve analysis of fine PVC aggregates are shown in the Table 6. The potable water was used for mixing and curing the concrete.

Table 2. Sieve analysis of coarse aggregate (8/16)

N°	Aperture size (mm)	Weigh retained (kg)	Percentage of retained weight (%)	Cumulative retained (%)	Percentage of coarse aggregate (%)
1	20	0.00	0.00	0.00	100.00
2	16	1.392	43.50	43.50	56.50
3	12.5	0.954	29.81	73.31	26.69
4	10	0.527	16.47	89.78	10.22
5	8	0.228	7.13	96.91	3.09
6	6.3	0.085	2.66	99.56	0.44
7	5	0.010	0.31	99.88	0.13
	Pan	0.003	0.09	99.97	0.03
	Total	3.20	≈100	Sum	197.09

Table 3. Sieve analysis of coarse aggregate (16/25)

N°	Aperture size (mm)	Weigh retained (kg)	Percentage of retained weight (%)	Cumulative retained (%)	Percentage of coarse aggregate (%)
1	40	0	0.00	0.00	100.00
2	25	0.018	0.36	0.36	99.64
3	20	1.064	21.28	21.64	78.36
4	16	2.316	46.32	67.96	32.04
5	12.5	1.46	29.20	97.16	2.84
6	10	0.103	2.06	99.22	0.78
7	8	0.024	0.48	99.70	0.30
8	6.3	0.01	0.20	99.90	0.10
9	5	0.002	0.04	99.94	0.06
	Pan	0	0.00	99.94	0.06
	Total	5.00		Sum	314.12

Table 4. Sieve analysis of fine aggregate (sand)

N°	Aperture size (mm)	Weigh retained (kg)	Percentage of weight retained (%)	Cumulative retained (%)	Percentage of coarse aggregate (%)
1	5	0.006	0.60	0.60	99.40
2	2.5	0.02	2.00	2.60	97.40
3	1.25	0.068	6.80	9.40	90.60
4	0.63	0.231	23.10	32.50	67.50
5	0.315	0.538	53.80	86.30	13.70
6	0.160	0.123	12.30	98.60	1.40
7	0.08	0.012	1.20	99.80	0.20
	Pan	0.001	0.10	99.90	0.10
	Total	1.00		Sum	370.20

Table 5. Properties of Fine and Fiber PVC

Properties	Values	
	Fine	Fiber
Colour	Light grey	Light grey
Shape	Powder	Fiber
Type	Crushed	Crushed
Maximum Size (mm^2/mm)	2.5	3×8
Bulk Density (kg/m^3)	1.38	1.38
Apparent Density (kg/m^3)	1.2	1.12
Fineness Modulus	3.00	/

Table 6. Sieve analysis of fine PVC

N°	Aperture size (mm)	Weigh retained (kg)	Percentage of weight retained (%)	Cumulative retained (%)	Percentage of coarse aggregate (%)
1	5	0.00	0.00	0.00	100.00
2	2.5	0.001	0.10	0.10	99.90
3	1.25	0.028	2.80	2.90	97.10
4	0.63	0.269	26.90	29.80	70.20
5	0.315	0.410	41.00	70.80	29.20
6	0.160	0.263	26.30	97.10	2.90
7	0.08	0.027	2.70	99.80	0.20
	Pan	0.001	0.10	99.90	0.10
	Total	1.00		Sum	399.50

2.2 Concrete mixtures

The concrete mix was designed according to the standard NF EN 206/CN, by adopting the Dreux-Gorisse method [25], for the purpose to obtain a concrete of minimum compressive strength at twenty-eight days of 25 MPa. The mixed proportions of all concrete mixes are shown in Table 7. A total of thirty-six concrete specimens were prepared and manufactured by using water to cement (W/C) ratio of 0.5. For the contained PVC concrete mixtures, the PVC quantity aggregate was calculated as a volume replacement of natural sand. In this experimental study, three replacement ratios of 5%, 10% and 15% were considered. After demolding the samples at 24 hours. They were cured for 7 and 28 days, inside the laboratory until the testing day in favorable conditions, at an ambient temperature of 23°C ± 3, and an average humidity of 40%. Figure 3 shows the concrete mixes with different PVC waste and the manufactured samples.

Table 7. The used mixes details for a cubic meter of concrete

Mix design		Water (kg)	Cement (kg)	Fine and coarse aggregates (kg)			PVC aggregate (kg)
				Sand	(8/16)	(16/25)	
Ordinary concrete	OC	175	350	730	670	447	/
Concrete with fiber PVC	CFIB5	175	350	704	670	447	20
	CFIB10	175	350	667	670	447	39
	CFIB15	175	350	630	670	447	58
Concrete with fine PVC	CF5	175	350	704	670	447	20
	CF10	175	350	667	670	447	39
	CF15	175	350	630	670	447	58

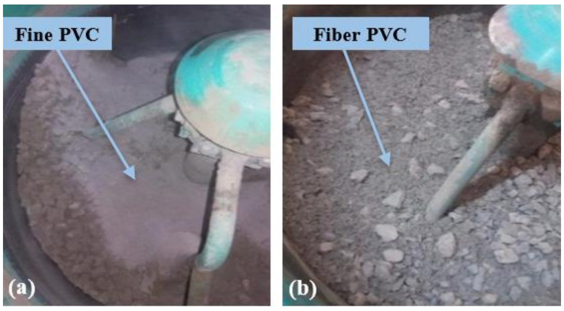


Figure 3. Concrete mixtures with different PVC waste: (a) Fine PVC aggregate and (b) Fiber PVC

3. RESULTS AND DISCUSSION

The behavior of ordinary concrete (OC) and the concrete with fiber and fine PVC (CFIB and CF), was assessed in terms of strength and workability by conducting slump test, compressive strength and split tensile strength tests. The obtained results are presented and discussed below this section. In the Table 7, the reported measurements have been carried out in triplicate.

Table 8. Values of weight and slump for various mixtures of concrete

Mix design		Weight (kg)	Slump (mm)
Ordinary Concrete	OC	15.55	65
Concrete with Fiber PVC	CFIB5%	15.26	55
	CFIB10%	15.2	45
	CFIB15%	15.06	30
Concrete with Fine PVC	CF5%	15.47	49
	CF10%	15.24	41
	CF15%	14.98	28

3.1 Workability for various concrete mixtures

The workability test (slump test) is a test used to determine the concrete consistency. The test gives an indication of how much water was used in the mixture [26]. The workability test results and weight values at 28 days for the various mixes of concrete are shown in Table 8. The workability variation of different concrete mixtures is shown in Figure 4. The results reveal that there is a remarkable decrease in the weight of concrete when the recycled PVC is added as aggregate; owing to the low density of PVC aggregates. Therefore, a decrease in the value of workability was observed. The reduction was ranged from 15% to 57%, and then compared to the ordinary concrete (OC). The decrease was less remarkable for concrete with PVC fibers, due to the smoothness form of the PVC fiber aggregates, which increase interfacial debonding between PVC aggregate and cement paste. It can also be explained by the concrete containing fiber PVC aggregates has more free water than a mixture with fine PVC. This is because of the non-absorptive nature of the PVC fiber, contrary to fine PVC, which traps more water.

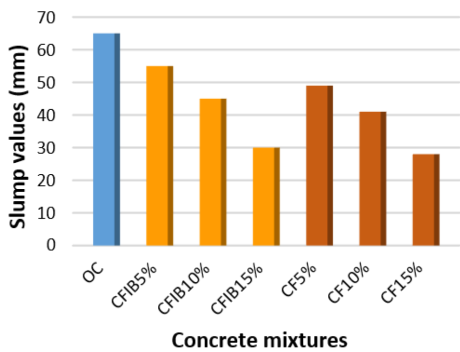


Figure 4. Slump variation of mixtures

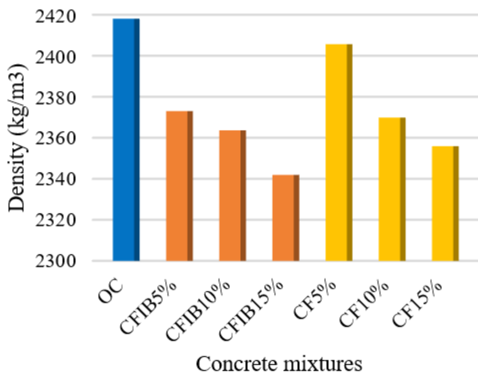


Figure 5. Density variation of mixtures

Figure 5 shows that, the workability of the concrete decreases as the PVC aggregate ratio increases. The mixtures containing PVC fibers (larger particle size) showed a higher slump, compared to those with a smaller particle size (PVC fines). In contrast, all the mixes containing PVC waste showed a smaller value than the reference concrete (containing only natural sand). It is clearly perceptible that the rheological behavior of concrete was significantly influenced when PVC waste was included. Furthermore, no segregation was observed in any mixes, even for concrete made with natural sand.

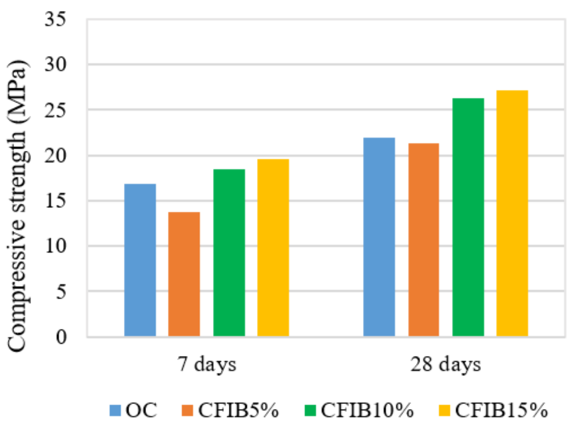
3.2 Compressive strength

The concrete compressive strength was measured according to the standard EN 196-1 [27] by using a digital compression machine type Controls-MCC8 (Controls S.p.A, Liscate, Italy) with a capacity of 3000 kN (Figure 6a). The cylindrical samples were 160×320 mm^2 (diameter × length) of dimensions and the average of three specimens was registered at 7 and 28 days for each mix. The results of concrete compressive strength of all mixes are presented in Table 9. It can be seen that at 7 days age, the compressive strengths of the concrete containing PVC waste fines were reduced with increasing the ratio of PVC aggregates. However, at twenty-eight days the compressive strength was enhanced by adding PVC wastes. Nevertheless, the increasing of sand replacement ratio reduces the compressive strength of the concrete. It reached 47% for the lowest sand replacement ratio.

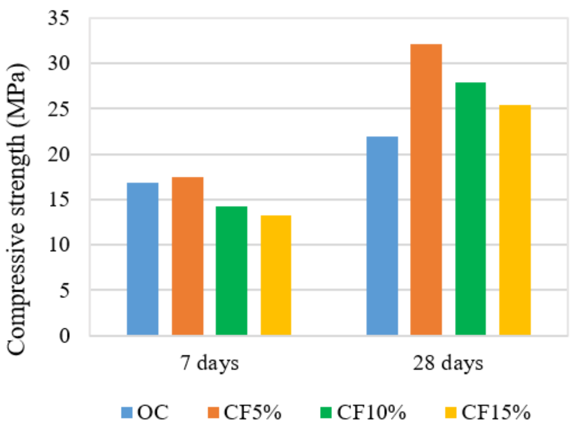
Figure 6. (a) Compressive strength test and (b) Split tensile strength test

Table 9. Compressive strength of concrete mixtures

Mix design		Sand content (kg/m^3)	PVC content (kg/m^3)	Compressive strength (MPa)	
				7 days	28 days
Ordinary Concrete	OC	730	0	16.88	21.98
Concrete with fiber PVC	CFIB5%	704	20	13.8	21.37
	CFIB10%	667	39	18.42	26.26
	CFIB15%	630	58	19.64	27.15
Concrete with fine PVC	CF5%	704	20	17.42	32.18
	CF10%	667	39	14.22	27.87
	CF15%	630	58	13.25	25.41



(a) Compressive strength of concrete with PVC Fiber



(b) Compressive strength of concrete with PVC Fine

Figure 7. Compressive strength graphs for all mixtures

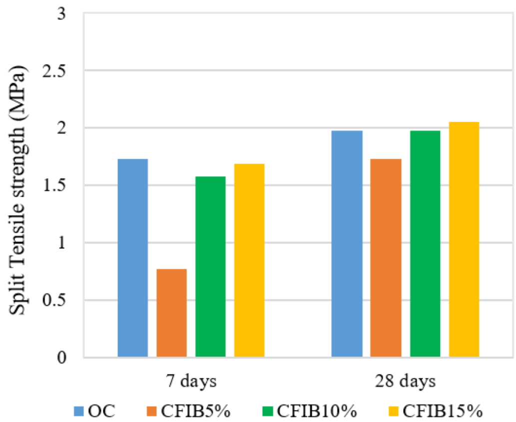
Then, it decreased to 16% for a higher ratio of 15%. While, its compressive strength remains higher than the concrete with natural sand. This is because the finer particle size of waste PVC, has a more intense activity with the cement and the pore filling is more efficient. But, increasing of PVC aggregates ratio, causes more air content in the mixture, causing a decrease in mechanical strength as reported in previous studies [4]. In contrast, at all test ages, the compressive strengths of mixes containing PVC fibers were enhanced with increasing the ratio of PVC aggregates. It reached 24% for the highest replacement ratio. This was due to the angular shape and larger sizes of the PVC aggregate, compared with ordinary concrete OC (natural sand). In addition, the test results (Figure 7) reveal that, for low replacement ratio, the compressive strength of mixtures was lower for concrete containing PVC fibers than mixture with PVC fines. This is because, as the plastic fibers have practically lower water absorption capacity. The water accumulates in the mixture, making it more porous after curing. The supplementary porosity causes a reduction in the mechanical strength of mixes in terms of compression. In addition, the coarser size of the PVC fiber aggregates leads to reduce in the filling of the concrete. However, some authors have signaled a different tendency [20, 28, 29]. They have found a decrease in the compressive strength of concrete for both low and high sand replacement ratios. Probably, this dissimilarity is due to the source of plastics used in the study and the sand replacement ratio, which leads to different behaviors of concrete mixtures.

3.3 Split tensile strength

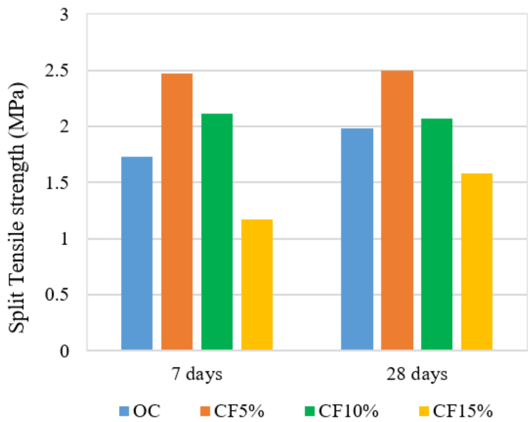
The split tensile strength was measured at 7 and 28 days. The tests were carried out by a digital compression machine type CONTROLS-MCC8 according to the standard NF EN 206–1/CN / December 2014 (Figure 6b). The obtained tensile strength of all specimens is shown in Table 10 (the reported measurements have been carried out in triplicate). In the current study, the concrete tensile strength of mixtures was measured by replacing 5%, 10% and 15% of the natural sand with PVC aggregates. The test results show that the addition of PVC fiber reduces the tensile strength. This is due to the weak bond between the PVC fiber aggregates and the cement matrix. However, increasing the replacement ratio of PVC fiber improves the tensile strength of mixtures, but does not exceed the ordinary concrete.

Table 10. Split tensile strength of concrete mixtures

Mix designation		Sand content (kg/m3)	PVC content (kg/m3)	Split tensile strength (MPa)	
				7 days	28 days
Ordinary Concrete	OC	730	0	1.73	1.98
Concrete with fiber PVC	CFIB5%	704	20	0.77	1.73
	CFIB10%	667	39	1.58	1.98
	CFIB15%	630	58	1.69	2.05
Concrete with fine PVC	CF5%	704	20	2.47	2.5
	CF10%	667	39	2.11	2.07
	CF15%	630	58	1.17	1.58



(a) Split tensile strength of concrete with PVC Fiber



(b) Split tensile strength of concrete with PVC Fine

Figure 8. Split tensile strength graphs for mixtures

This probably is due to an increase in the fiber content, which leads to an increase in the contact surface (cement-PVC), which improved the concrete matrix. It is observed, that the adding of PVC waste as fiber with a ratio of 5% decreases tensile strength by 13%. However, for 15% of replacement ratio the tensile strength of mixture increases up to 4%.

The study also revealed that for concrete mixes containing PVC wastes as a powder with a low ratio of 5%, shows an improvement in split tensile strength, compared to the ordinary concrete (Figure 8). The increasing was around 26%. On the other hand, the excessive replacement by PVC fine reduces the concrete tensile strength. For instance, the replacement ratios of 10% and 15%, a decrease in tensile strength was obtained at about 5% and 20%, respectively, compared to the ordinary concrete. This is mainly attributed to the same factors causing the decrease in compressive strength with addition of PVC aggregate. This later causes more air content in the mixture, which induces a decrease in mechanical properties.

The obtained results of mixtures containing PVC fine are in good agreement with the majority of previous studies [25-27, 30-34]. Figure 9 shows the correlation between compressive strength and tensile strength at 28 days. For both types of PVC wastes, it is clearly visible that the tendency is practically linear with an excellent correlation. The following relationship between compressive strength (f_c) and split tensile strength (f_t) is proposed for fiber PVC concrete:

$$f_c = 18.459\, f_t + 10.515 \quad (1)$$

where the correlation coefficient is R²=0.9956.

However, for fine PVC concrete, the proposed relationship is:

$$f_c = 7.3046 f_t + 13.512 \quad (2)$$

where the correlation coefficient is $R^2 = 0.9628$. The values of the correlation coefficient (R^2) indicate that there is a good correlation between the compressive strength and the split tensile strength. The linear curve slope is greater in the case of mixtures with fine PVC waste than the fiber PVC. Thus, for the same split tensile strength, the compressive strength is higher for the mixtures with fine PVC than the mixture with fiber PVC. Furthermore, for the same compressive strength, the split tensile strength is greater for mixtures containing fiber PVC. This is due to the complimentary participation of PVC fiber in tensile strength.

4. STATISTICAL STUDY

4.1 The factorial experimental results

The variance analysis enables to evaluate the effect factors contribution to the responses, as indicated in Table 11. The statistical analysis of the obtained results allowed to evaluate the influence of each factor. In this study, the proposed models have high correlation coefficients, which is greater than 0.7.

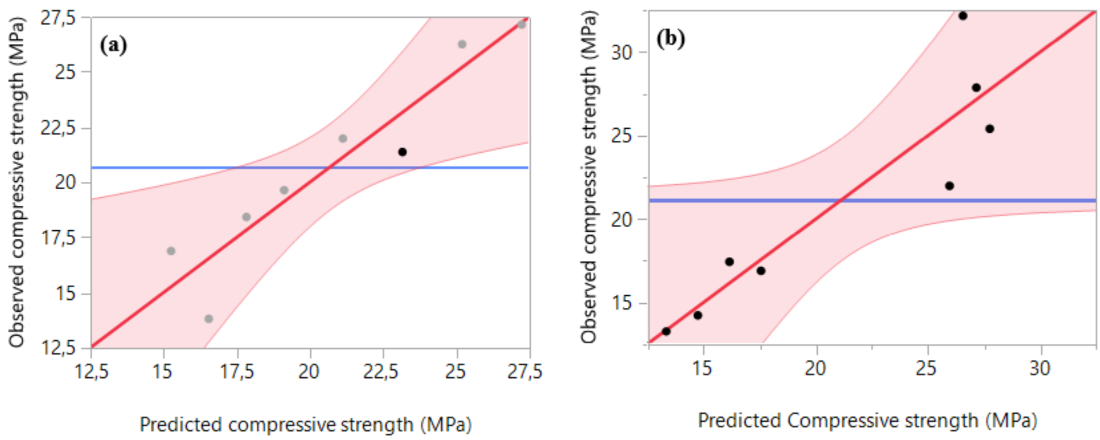
This means that the obtained experimental results and the proposed models have a good correlation. Meanwhile, the established models allow the prediction of the effect of sand substitution by PVC waste (fiber and fine) and the concrete age on the mechanical strength.

Figure 9 shows the relationship between the predicted and the measured compressive strengths with confidence intervals of 95%. The correlation coefficients were the order of 0.889 and 0.829 for concrete with fiber and fine PVC waste, successively. This indicates that the models fit to the experimental results is very well.

The correlation between the compressive strength and the density of the hardened concrete is illustrated in Figure 10. The relationship and the correlation coefficient are given for both concrete mixtures.

Table 11. Fitting results summary

	Fiber PVC	Fine PVC
Coefficient of determination R^2	0,889203	0.82999
Adjusted R^2	0,806105	0.702483
Root Mean Square Error (RMSE)	1,991105	3.735085
Mean of response	20,6875	21.15125



(a) Mixtures with fiber PVC (b) Mixtures with fine PVC

Figure 9. Correlation between the observed and the predicted compressive strength

The analysis of the variance for each type of PVC wastes is represented in Table 12. The statistical significance of the developed models should be evaluated using the Fisher test for a confidence interval of 95% and an error of 0.05. The obtained critical Fisher ratio (Fcr) is 6.59 for concretes that were made by fiber and fine PVC wastes. The obtained results reveal that the F-ratio>Fcr. This means that the regression models are valid.

Table 12. Variance analysis (ANOVA) for derived models

Mixes	Source	Degree of freedom	Sum of squares	Mean square	F-ratio
CFIB	Model	3	127,2685	42,4229	10,7007
	Error	4	15,8580	3,9645	
	Total	7	143,1265		
CF	Model	3	272.4330	90.8110	6.5093
	Error	4	55.80345	13.9509	
	Total	7	328.2364		

4.2 Mathematical models

In this section, the obtained independent variables (7 days and 28 days) and the substitution ratio (0%, 5%, 10% and 15%) are introduced in the software (JMP Pro) [35]. All the proposed models were based on a global factor approach. The mathematical equation proposed to predict the compressive strength is valid for a wide range of mixtures. The variable parameters were the age of the concrete and the substitution ratio ranged from 0% to 15%.

The mathematical relationship of the compressive strength for specimens with PVC fiber is given by:

$$f_c = 20.688 + 3.5025\left(\frac{(Age - 17.5)}{10.5}\right) + 2.498\left(\frac{PVC_{ratio} - 7.5}{7.5}\right) + 0.563\left(\frac{(Age - 17.5)}{10.5} + \frac{PVC_{ratio} - 7.5}{7.5}\right) \quad (3)$$

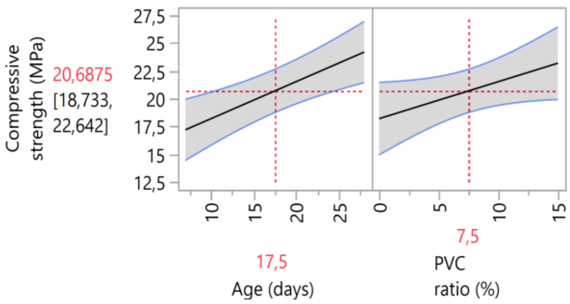
However, the mathematical relationship of the compressive strength for specimens with PVC fine is given by:

$$
\begin{aligned}
f_C = 21.151 &+ 5.708\left(\frac{(Age - 17.5)}{10.5}\right) \\
&+ 0.608\left(\frac{PVC_{ratio} - 7.5}{7.5}\right) \\
&+ 1.505\left(\frac{(Age - 17.5)}{10.5}\right. \\
&\left. + \frac{PVC_{ratio} - 7.5}{7.5}\right)
\end{aligned} \tag{4}
$$

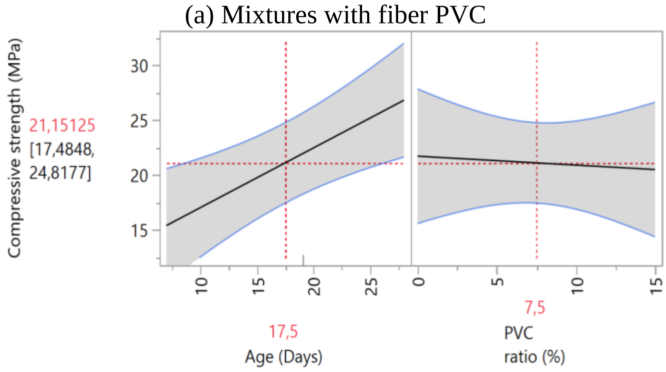
Although the developed models are based on a limited number of data, they can be worthwhile to comprehend the effect of each parameter (age of concrete and substitution ratio) on the behavior of concrete made with PVC wastes.

4.3 Analysis of the compressive strength results

Figure 10 shows the different types of plots developed by analyzing the obtained compressive strength results considering the factors of the PVC ratio and the concrete age. The obtained results indicate that the strength of the concrete increases as the concrete age. However, on the one hand, for mixtures made by adding fiber PVC waste, the increase in the substitution ratio shows a slight increase in the compressive strength of concrete. On the other hand, in the case of the substitution of sand by fine PVC waste, the increase in the substitution ratio leads to a decrease in compressive strength.



(a) Mixtures with fiber PVC

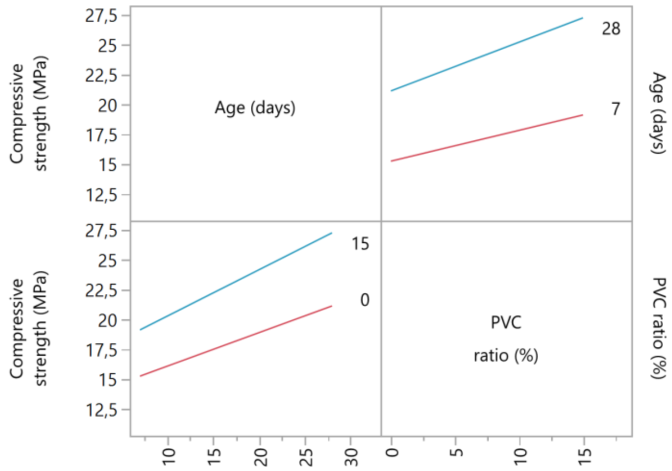


(b) Mixtures with fine PVC

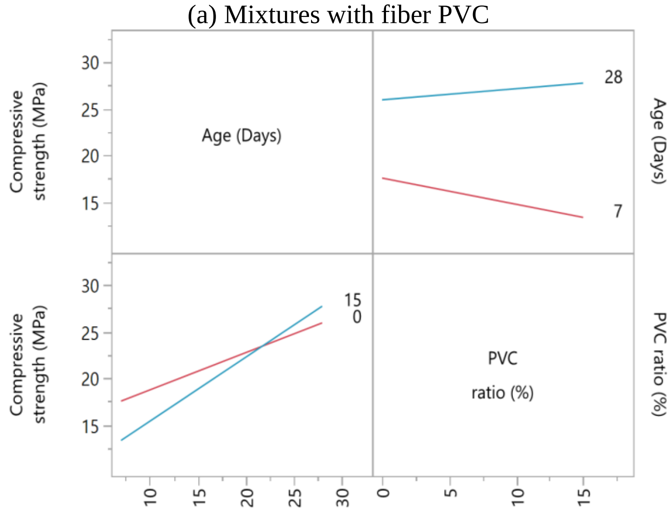
Figure 10. Main effect plot for different concrete mixes

The interaction graphs of the response (compressive strength) taking into account the studied factors (age, PVC ratio) are presented in Figure 11.

Figure 10(a) shows that the interaction diagrams are not parallel. This means that there is a slight interaction between the substitution ratio of fiber PVC and the age of concrete. However, for the concrete with fine PVC, the interaction diagrams of the two factors are crossed. This indicates that the interaction effects of both factors on the response are significant. The effect of concrete age on the response is affected by the values of the second factor (fine PVC ratio). For instance, the introduction of 15% fine PVC increased the compressive strength of concrete by 2%.



(a) Mixtures with fiber PVC



(b) Mixtures with fine PVC

Figure 11. Interaction plot of compressive strengths for different concrete mixes

5. CONCLUSIONS AND RECOMMENDATIONS

The present experimental study aimed to a better understanding the mechanical behavior of concrete made by PVC wastes as replacement of natural sand. Three sand replacement ratios of PVC waste were considered (5%, 10%, and 15%). Two forms of PVC wastes were studied (Fine and Fiber). Based on the obtained results, the following conclusions have been drawn:

(1) The rheological concrete behavior was influenced by the addition of PVC waste. Therefore, it was affected by the PVC aggregates shape and the sand replacement ratio.

(2) The concrete made with PVC fiber presents a lower workability than the concrete made with fine PVC.

(3) The concrete density was reduced by the PVC addition. This reduction is greater for the mixtures with fiber PVC aggregates.

(4) The incorporation of PVC waste in concrete as a partial replacement for natural sand leads to a decrease in the workability of fresh concrete.

(5) The addition of PVC fiber to the concrete improves the compressive strength. More as the replacement ratio increases, the compressive strength also increases.

(6) When PVC fine aggregate is incorporated with a moderate ratio, an increase in compressive strength is obtained. However, a decrease in compressive strength is registered with the increase in fine PVC replacement ratio.

(7) A similar evolution of the compressive strength is observed in tensile strength, when adding fiber and fine PVC. Except that, the gain in tensile strength for mixes with PVC fiber is practically insignificant.

(8) The PVC waste addition to concrete mixes presents better mechanical performance factor results for high PVC fiber and moderate PVC fine ratios.

(9) The PVC waste addition does not only cut down the concrete cost, but also contributes to the disposal of waste materials, pollution limitation, and the moderation of energy consumption. It can also, participates to improve the concrete behavior in compression and tensile. It is only a matter of adopting the optimal replacement ratio.

Based on the obtained results, the optimal replacement ratio should be within 5% for fine PVC and 15% for PVC fiber. It would be desirable to complete this experimental study through further investigations for other PVC waste ratios in order to determinate the optimal ratios. The future works are also to evaluate the responses of the structural elements made by concrete containing PVC wastes, such as beams and columns.

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