DOI: 10.2478/sspjce-2024-0008

Relationship between Porosity-Ultrasonic Pulse Velocity and Water Absorption of Concrete Containing Plastic and Rubber Waste by Full Factor Desing

Ameur Belmouhoub[1*], Assia Abdelouahed[1]

[1]University of 20 Août 1955-Skikda
Faculty of Technology, Department of Civil Engineering Laboratory LMGHU
*e-mail : a.belmouhoub@univ-skiksa.dz,   a.abdelouahed@univ-skikda.dz

Abstract

Utilizing waste plastic and rubber in civil engineering is one of the most environmentally friendly and economically advantageous options. In this work, the aim was to study the relationship between porosity, ultrasonic pulse velocity, and water absorption using waste plastic and rubber in ordinary concrete and analyze the results with a program called JMP, where cement was replaced with rubber as a mass substitute in proportions of 2% and 4% and sand was replaced with plastic as a mass substitute in proportions of 2%, 4%, and 6%. The tests used were ultrasonic speed at 28 days, porosity, water absorption by total immersion, and sorptivity. The findings reveal that as the amount of rubber and plastic increases, the speed of ultrasonic decreases. Additionally, higher amounts of rubber and plastic lead to increased porosity, water absorption by total immersion, and sorptivity. The speed of ultrasonic pulses varies between 4065.04 m/s and 3838.90 m/s, porosity levels range from 11.63% to 13.44%, water absorption by total immersion falls between 5.40% and 6.16%, and sorptivity ranges from 9.93 g/m^2 to 13.99 g/m^2. Furthermore, the addition of rubber and plastic waste causes large voids and cracks to form inside the concrete structure. These voids and cracks can increase the porosity of the concrete, which raises the rate of water absorption and lowers the ultrasonic pulse velocity, according to scanning electron microscopy (SEM) data. After assessing the data, it was determined that the numerical simulations for various factors such as ultrasonic pulse velocity, porosity, water absorption by total immersion, and water absorption by capillary exhibited strong correlation, with calculated coefficients R^2 near 1.

Keywords: rubber, plastic, concrete, microstructure, factorial desing

1 Introduction

Plastic and rubber waste are major problems in today's world, with many negative effects on the environment [1]. The accumulation of rubber tires is on the rise [2] , as the number of tires used in the world each year has reached more than 13.5 million tons [3,4]. While the amount of plastic waste in the world is estimated at 300 million tons annually [5]. This waste takes a long time to decompose, causing damage to the environment and human health [6]. However, there are new opportunities to exploit this waste; particularly in the concrete sector. One strategy to enhance sustainability and minimise the use of natural resources is to include waste plastic and rubber in concrete [7, 8, 9, 10, 11, 12, 13]. This waste can be processed into fine particles or granules and mixed with cement, granules, and water to form the concrete mix. Adding these wastes can improve the flexibility and thermal insulation capacity of concrete. Using concrete with plastic and rubber waste, also reduces the amount of waste sent to landfills or combustion, helping to preserve the environment. Senhadji et al. [14] used plastic PVC in concrete to replace the sand with rations of 30, 50, and 70% by volume, which led to a decrease in the ultrasonic pulse velocity at ages 28 and 90 with increasing the level of plastic PVC. Also, Akçaözoğlu et al. [15] used three types of plastic (PE, PP, and PVC) in proportions of 25%, 50%, and 75%. The results indicated that each time the percentage of this waste increased, the ultrasonic speed decreased. According to the authors, Saikia and Brito [16], the higher permeability of concrete with plastic aggregate is attributed to the expansion of porosity resulting from the loose connection between the cement paste and the plastic aggregate. Concrete with PET aggregate showed higher percolated porosity compared to concrete with PC aggregate at increased replacement levels (10%, 20%, and 50%). As well, it was also observed that water absorption rose as the plastic content increased. Concrete with 50% recycled plastic aggregates exhibited a significant increase in water absorption, approximately 117% higher than conventional concrete. The introduction of plastic aggregates heightened porosity in the concrete, resulting in a substantial shift in water absorption behavior. Colangelo et al. [17], found that the porosity of concrete rose by approximately 19.5%, 31.2%, and 40.1% when the substitution ratio increased to 10%, 20%, and 30%, respectively. Similarly, the water absorption also surged from 9.0% to 15.2% accordingly. This was attributed to the greater presence of trapped air stemming from the higher plastic aggregate content, leading to the formation of larger pores within the concrete structure. Coppola et al. [18] and Albano et al. [19] found that the higher water absorption for concrete contains waste plastic compared to control concrete. Kou et al. [20] used plastic PVC granules as a substitute for sand, finding that water absorption rose as the amount of plastic PVC increased. Senthil et al. [21] conducted a study in which varying proportions (0%, 10%, 20%, 30%, 40%, and 50%) of waste E-plastic electronic parts were used to substitute natural coarse aggregates by volume in concrete. The findings revealed that as the amount of E-plastic in the concrete increased, there was a corresponding increase in capillary water absorption compared to the control concrete. Chidiac and Mihaljevic [22] found that the capillary water absorption rate rose as the proportion of HDPE (high-density polyethylene) and LDPE (low-density polyethylene) plastics increased. On the other hand, Kumar and Dev [23] used rubber as a powder in proportions (0, 10, 15, 20, 25, and 30%) for the substitution of fine aggregates. They found that the ultrasonic velocity decreased as the percentage of rubber increased. Djebien et al. [24] observed that when the amount of tire rubber increased from 1% to 4%, the ultrasonic pulse velocity decreased by 1.10% and 10.11%, respectively. Si et al. [25] found the ultrasonic velocity with rubber waste ranges from 4006 m/s to 4037 m/s, which is lower than the 4308 m/s for ordinary concrete. The incorporation of rubber into concrete created voids in the concrete structure, causing increased diffusion time, which led to a decrease in ultrasonic velocity. This is also explained by the decrease in adhesion between the rubber tire rubber (RTR) and the cement paste, which leads to the occurrence of micro-cracks in the concrete, which in turn leads to raising its porosity and slow down the pulse velocity. Ramdani et al. [26] observed that the higher the rubber content in the concrete, the lower the pulse velocity. Khan and Khitab [27] findings indicate that higher rubber content leads to an increase in porosity. It was found that the crumb rubber acted as an air-entraining agent, boosting the porosity of the concrete. According to Turatsinze and Garros [28], the replacement of the natural aggregates with 25% rubber led to an increase in porosity of 30% compared to the control concrete. This increase is due to the increase in the percentage of air in the concrete. Gupta et al. [29] observed that the water absorption of concrete containing rubber increased with an increase in the percentage of rubber ash. The water absorption increased from 1.08% to 1.26% for concrete containing 0% and 20% of rubber ash, respectively, with the same w/c ratio at 28 days. Yilmaz and Degirmenci [30], and Ganjian et al. [31] observed an increase in the water absorption for all concrete containing waste rubber powder. According to Thomas et al. [32], rubberized concrete absorbs more water than ordinary concrete. Blessen et al. [33] conducted a study where they incorporated rubber powder in varying ratios (0 to 20%)

to replace fine aggregates in a mix. Their findings revealed that the sorptivity of the mix increased compared to the control mix, reaching a peak value of 0.7 mm with a 20% substitution.

Design of experiments JMP is a statistical tool used to design and assess experiments to test scientific theories. It also assists users in understanding the results and making well-informed decisions [34,35,36].

The aim of this study was to use waste plastic and rubber in concrete to study the relationship between porosity, ultrasonic pulse velocity, and water absorption. The results were analyzed using the JMP program, where sand was substituted for plastic in amounts of 2%, 4%, and 6%, and cement was substituted for rubber in amounts of 2% and 4%. Various findings from this study suggest that adding rubber and plastic to concrete increases its porosity, which raises water absorption and lowers ultrasonic velocity.

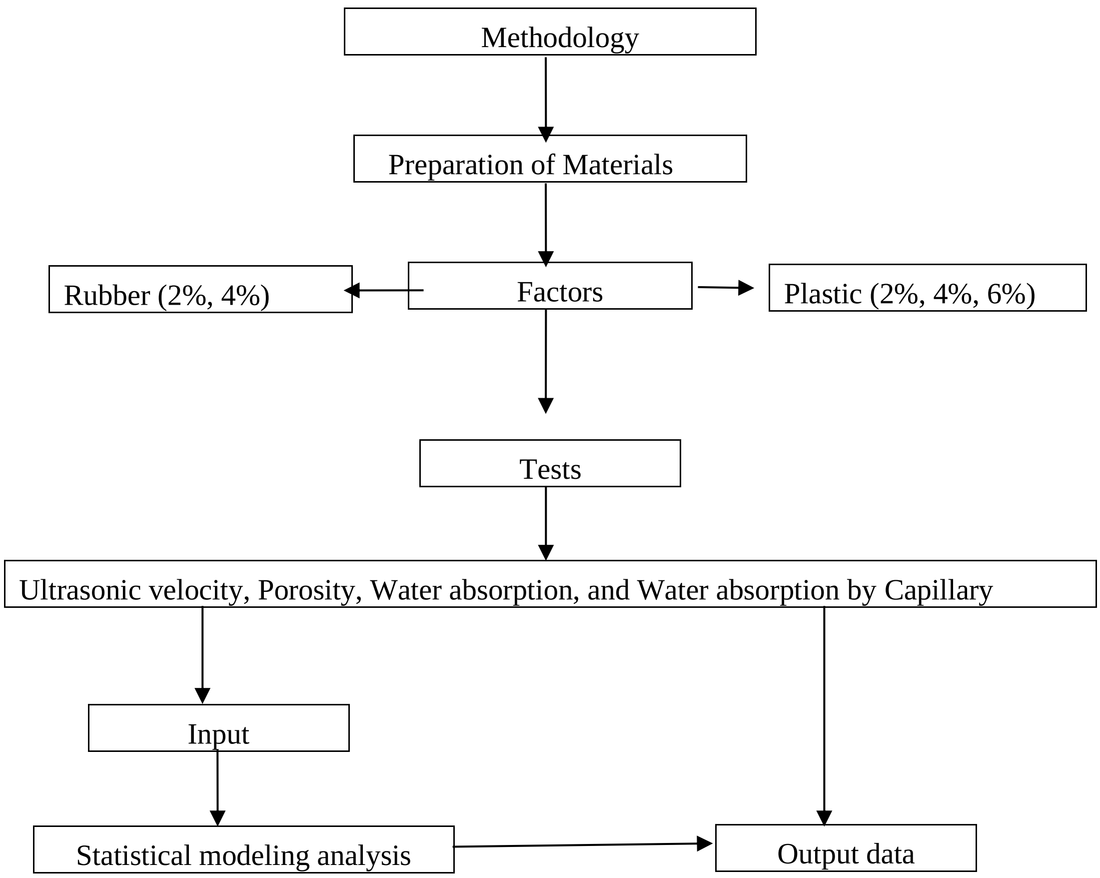


Figure 1: Flowchart illustrating the main stages of the research

2 Materials and methods

2.1 Materials

For this study, CRS CEMI-42.5 cement, brought from the Ain-Kebira (Setif) region of eastern Algeria, was employed. Its chemical and physical components are listed in Tables 1 and 2.

Table 1: Chemical composition of the cement

Designation	CaO	Al_2O_3	Fe_2O_3	SiO_2	MgO	Na_2O	K_2O	Cl	SO_3	C_3S	C_2S	C_3A	C_4AF
Content (%)	62.04	4.59	5.08	23.41	1.74	0.17	0.34	0.05	1.46	36.50	39.90	3.50	15.40

Table 2: Physical composition of the cement

Designation	**Value**
Apparent density (g/cm^3)	3.10
Absolute density (g/cm^3)	1.05
BSS (cm^2/g)	2800.20
Initial setting time (min	90
Final setting time (min)	260

Two different types of gravel were used: 3/8 and 8/15, and sand 0/3 was employed. The rubber waste utilized was in powder with a size of less than 0.08 mm, and it was treated for 20 minutes with 10% sodium hydroxide (NaOH). After that, it was given a water wash and dried in open air [23], as illustrated in Figure 2. In this study, plastic was also employed as fine aggregates, as depicted in Figure 2, with a diameter of 1 mm. Table 3 displays sand, gravel, rubber, and plastic physical and chemical characteristics.

Table 3: Characteristics of sand (0/3), gravel (3/8), gravel (8/15), and rubber

Characteristics	**Sand (0/3)**	**Gravel (3/8)**	**Gravel (8/15)**	**Rubber**	**Plastic**
Absolute density (g /cm^3)	2.55	2.66	2.66	0.94	1.67
Apparent density (g/cm^3)	1.62	1.36	1.42	0.34	0.33
Fineness modulus (%)	1.97	-	-	-	-
Sand equivalent (%)	81.61	-	-	-	-
Absorption (%)	2.5	0.99	0.99	-	-

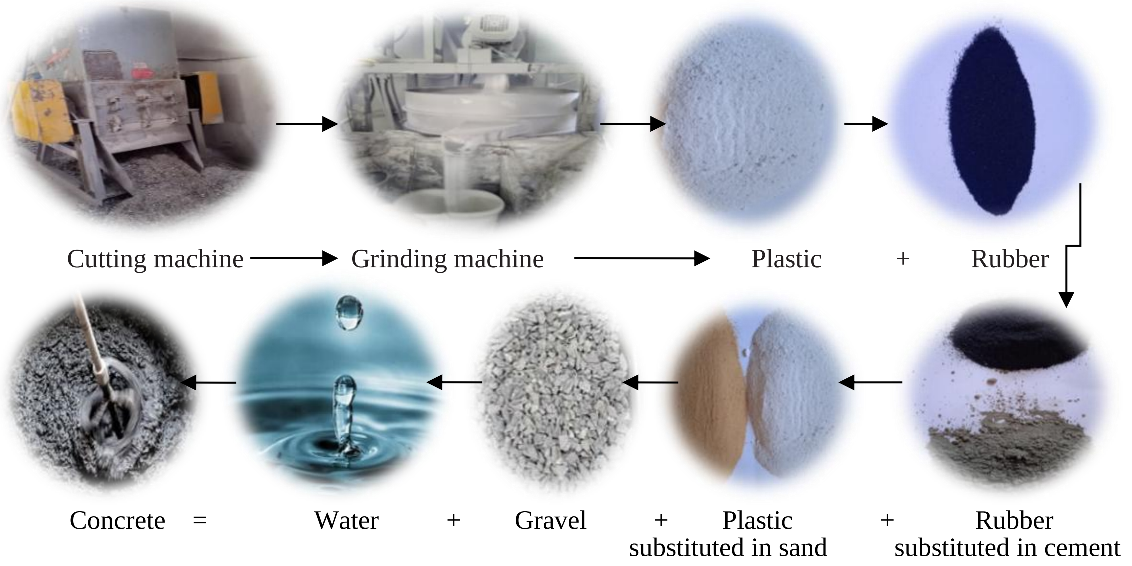


Figure 2: Flowchart showing the main stages of concrete manufacturing

Figure 3, shows the particle size curves for plastic, sand, gravel (3/8), and gravel (8/15). The particle size curves were created using the NF EN 933-1 standard.

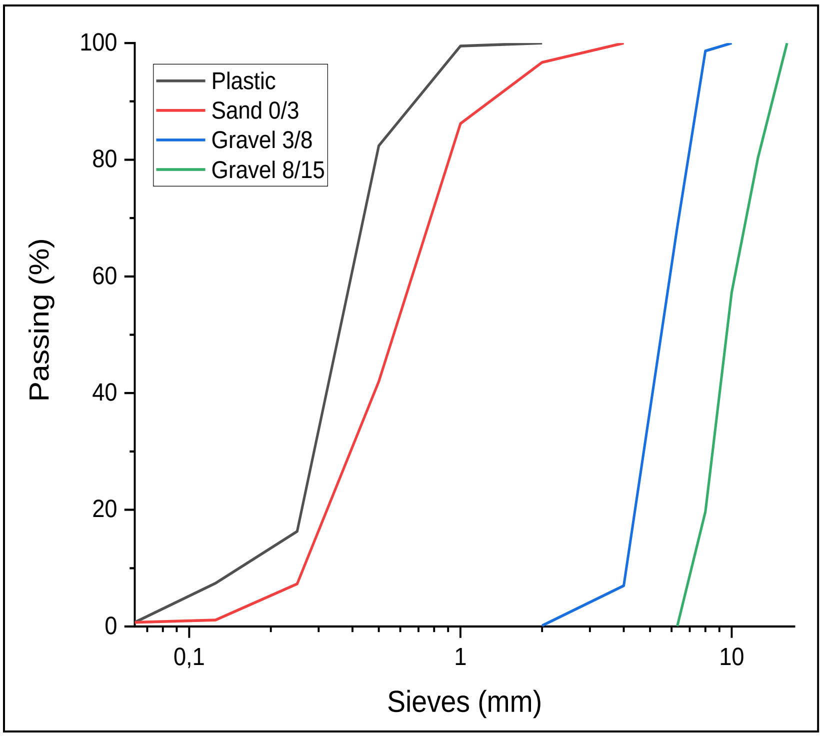


Figure 3: The particle size curve of the plastic, sand 0/3, gravel 3/8 and gravel 8/15

2.2 Experimental program

In this research, the Dreux-Gorisse method was utilized with a fixed water-to-cement ratio of 0.5. Cement was replaced with rubber at rates of 2% and 4%, while sand was replaced with plastic at ratios of 2%, 4%, and 6%. The preparation procedure began by sequentially adding gravel 8/15, gravel 3/8, sand, plastic aggregates, and rubber powder into the mixer. To ensure even distribution of rubber and plastic aggregates in the concrete elements, a dry mixing process was carried out for three minutes. Following this, cement was added to the mixture and further mixed for an additional minute. Water was then incorporated, and the components were mixed until homogeneous for two minutes. The specific compositions of the various mixtures being studied are outlined in Table 4. Subsequent to mixing, test samples were placed in molds at a temperature of 20 °C for 24 hours. After mixing, the specimens were taken out of the molds and stored in water until testing.

Table 4: The quantities of gravel, sand, cement, water, and rubber in one cubic meter

Mixes	**Gravel (8/15) (kg/m^3)**	**Gravel (3/8) (kg/m^3)**	**Sand (0/3) (kg/m^3)**	**Cement (kg/m^3)**	**Water (l/m^3)**	**Rubber (kg/m^3)**	**Plastic (kg/m^3)**
B0	689	219	741	400	209	0	0
B1	689	219	726.18	392	209	8	14.82
B2	689	219	711.36	392	209	8	29.64
B3	689	219	696.54	392	209	8	44.46
B4	689	219	726.18	384	209	16	14.82
B5	689	219	711.36	384	209	16	29.64
B6	689	219	696.54	384	209	16	44.46

Where:
B0: Ordinary concrete.
B1: Concrete containing 2% rubber and 2% plastic.
B2: Concrete containing 2% rubber and 4% plastic.
B3: Concrete containing 2% rubber and 6% plastic.
B4: Concrete containing 4% rubber and 2% plastic.
B5: Concrete containing 4% rubber and 4% plastic.
B6: Concrete containing 4% rubber and 6% plastic.

The dimensions of the molds used were 10 x 10 x 10 cm^3 for the test ultrasonic pulse velocity, porosity, and water absorption by total immersion, and 7 x 7 x 28 cm^3 for the test water absorption by capillary, as shown in Figure 4.

(a) (b) (c) (d)

Figure 4: Tests used in this study: (a) ultrasonic pulse velocity; (b) porosity; (c) water absorption by total immersion; (d) water absorption by capillary

Table 5: The tests used with standards

Tests	Standards
Ultrasonic pulse velocity	NF EN 12504-4
Porosity	NF EN 18-459
Water absorption by total immersion	NBN B 15-215:1989
Capillary water absorption	NF P 18-404

2.3 Mixture proportions

The current study aims to comprehend the distinct effects of plastic content and rubber on the characteristics of concrete. The relationship that the sum of factors produces is as follows:

$$Y=A_0+A_1A+A_2B+A_{12}AB \quad (1)$$

The expected response is denoted by (Y), while the model coefficients are represented by (A_0, A_1, and A_{12}).

3 Results and discussion

In this section, the relationship between porosity, ultrasonic pulse velocity, and water absorption using waste plastic and rubber in concrete is studied, and the results are analyzed using JMP software.

3.1 Relationship between porosity and ultrasonic pulse velocity at 28 days

After 28 days of curing, the relationship between the porosity and ultrasonic pulse velocity of concrete was determined by a linear regression equation created by analyzing test results using the software "Origin."

The relationship between pulse velocity and porosity is depicted in Figure 5.This response's equation is fc = -0.0089x +47.50. Porosity and ultrasonic pulse velocity have a strong association, with an R^2 = 0.90 correlation coefficient.

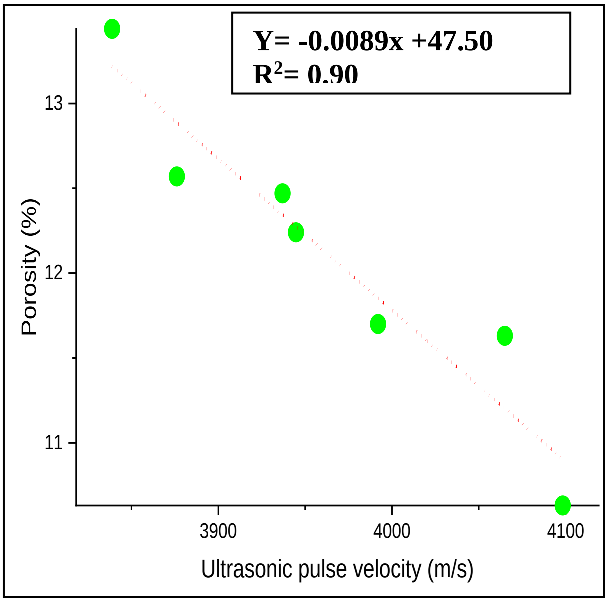


Figure 5: Intersection between porosity and pulse velocity

This suggests that porosity and ultrasonic pulse velocity are directly and linearly influenced by rubber and plastic powder. Additionally, expanding the pores raises the porosity, which lowers the ultrasonic pulse velocity. Consequently, the purpose of this connection is only to confirm that the experimental results obtained before modeling are correct.

3.2 Relationship between porosity and water absorption

Figure 6, shows the intersection between porosity and water absorption. The equation for this response is: fc = 1.41 x + 4.61.

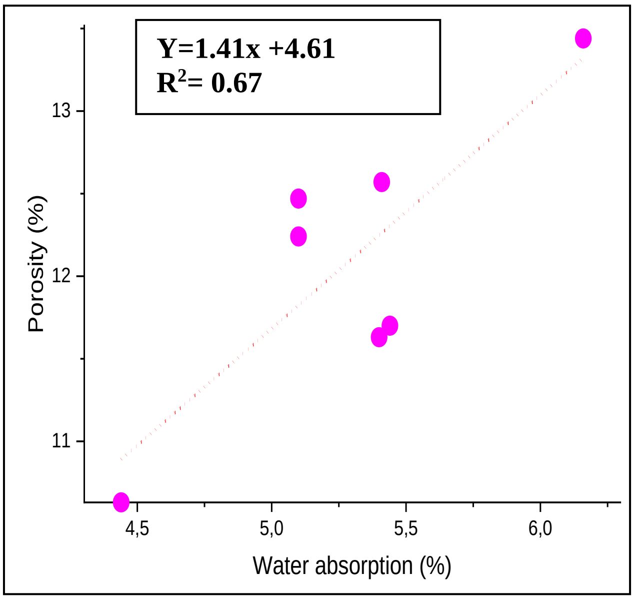


Figure 6: Intersection between porosity and water absorption

It shows an intermediate relationship between the results, with a correlation coefficient of R^2 equal to 0.67. Accordingly, 67% of the change in porosity is influenced by water absorption. The regression is positive, which indicates that increasing porosity causes an increase in water absorption. As the plastic and rubber aggregate content increases, the size of voids increases, resulting in a higher water absorption ratio.

3.3 Modeling of the mechanical response (UPV-PR-WA-WAC)

This section included the analysis of variance, summary of adjustments, and experimental results for ultrasonic pulse velocity, porosity, water absorption by total immersion, and water absorption by capillary.

3.3.1 Correlation: (UPV, PR, WA, and WAC)

There are six experiments total, with two levels for rubber and three for plastic presented in Table 6, and the summary of adjustments is presented in Table 7.
From Table 7, and Figure 7, the correlation coefficients ($R^2 > 0.9$) for ultrasonic pulse velocity, porosity, water absorption by total immersion, and water absorption by capillary. This demonstrates a strong correlation between the model records and the experimentally obtained responses.

Table 6: Experimental results

Mixes	**Rubber (%)**	**Plastic (%)**	**UPV (m/s)**	**PR (%)**	**WA (%)**	**WAC (g/m^2) at (24h)**
B1	2	2	4065.04	11.63	5.40	9.93
B2	2	4	3992.03	11.70	5.44	10.11
B3	2	6	3944.79	12.24	5.10	10.29
B4	4	2	3937.01	12.47	5.10	11.59
B5	4	4	3876.20	12.57	5.41	11.77
B6	4	6	3838.90	13.44	6.16	13.99

Table 7: Summary of adjustment

Tests	**UPV (m/s)**	**PR (%)**	**WA (%)**	**WAC (g/m^2)**
R^2	0,993	0,938	0.925	0.941
Adjusted R^2	0.984	0.846	0.812	0.853
Root of mean square error	10.069	0.260	0.167	0.588
Mean of response	3942.328	12.341	5.435	11.280

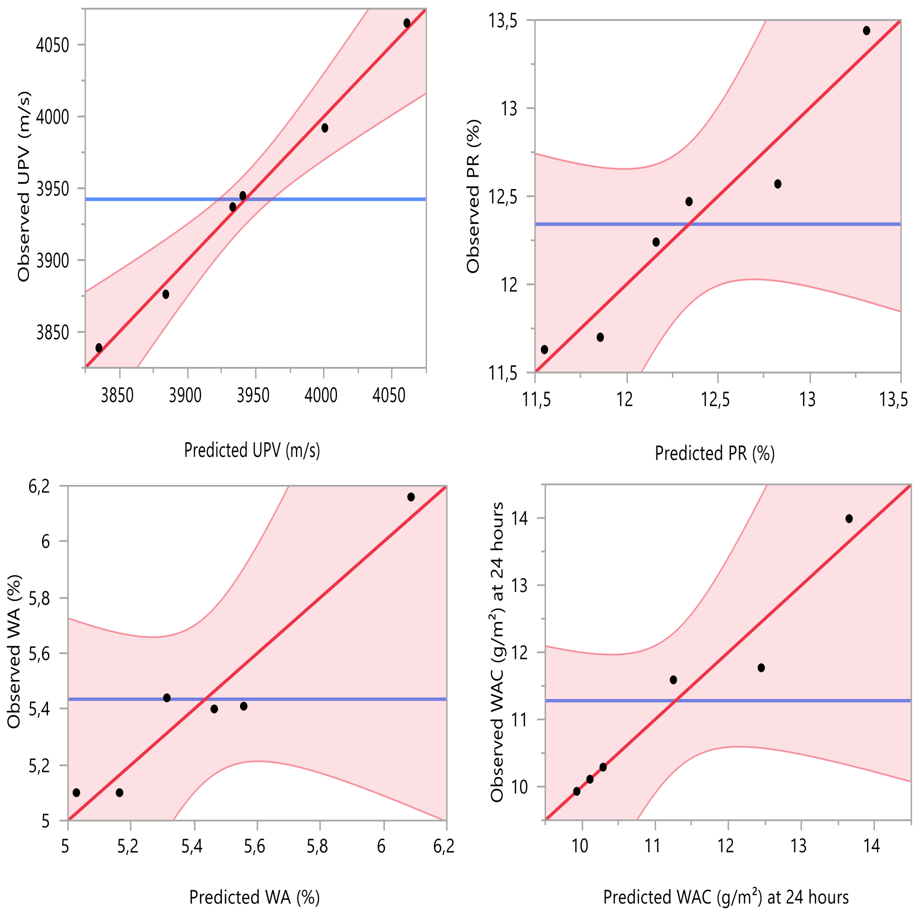


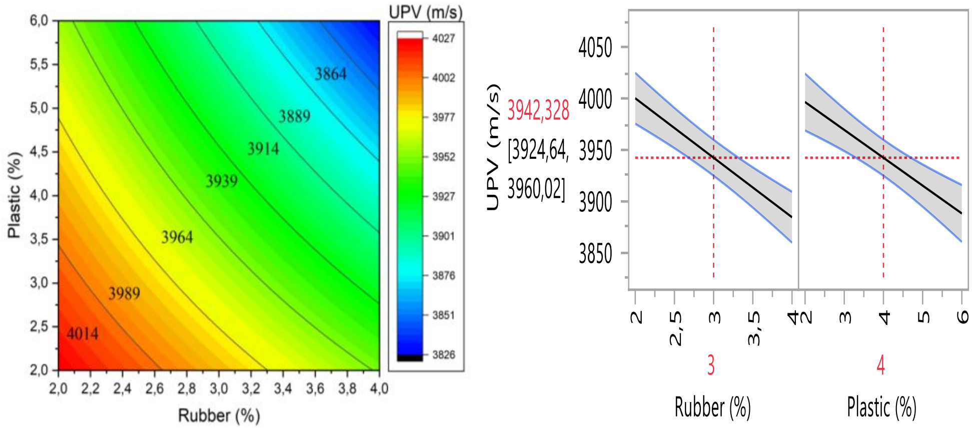
Figure 7: Evolution of correlation between observed and expected values

3.3.2 Ultrasonic pulse velocity (UPV)

Figure 8, displays the various plot types produced by examining the ultrasonic pulse velocity results while taking the rubber and plastic content into account. From Figure 8, it has been observed that the ultrasonic pulse velocity decreases from 4000 (m/s) to 3875 (m/s) due to the change in the level of rubber from 2% to 4% and the level of plastic from 2% to 6%. Specifically, the lowest ultrasonic pulse velocity was observed when the rubber content was less than 3.6% and the plastic content was less than 5.5%. This decrease in velocity can be attributed to the increased air content in the concrete mixture. Higher air content in the mixture leads to a reduction in ultrasonic velocity, as the presence of air pockets can interfere with the propagation of the ultrasonic waves, causing a decrease in velocity. These results are in agreement with those obtained by some authors [24, 37, 38]. Eq. 2 represents the ultrasonic pulse velocity mathematical model.

$$\text{UPV (m/s)} = 3942.32-58.29\,(\text{Rubber}-3) - 54.59\left(\frac{\text{Plastic}-4}{2}\right) + (\text{Rubber}-3)\left(\frac{\text{Plastic}-4}{2}\right)(-5.53) \qquad (2)$$

Rubber's and plastic's coefficients are (-58.29) and (-54.59), respectively, making it abundantly evident that these factors have a negative impact on this response.



(a) (b)

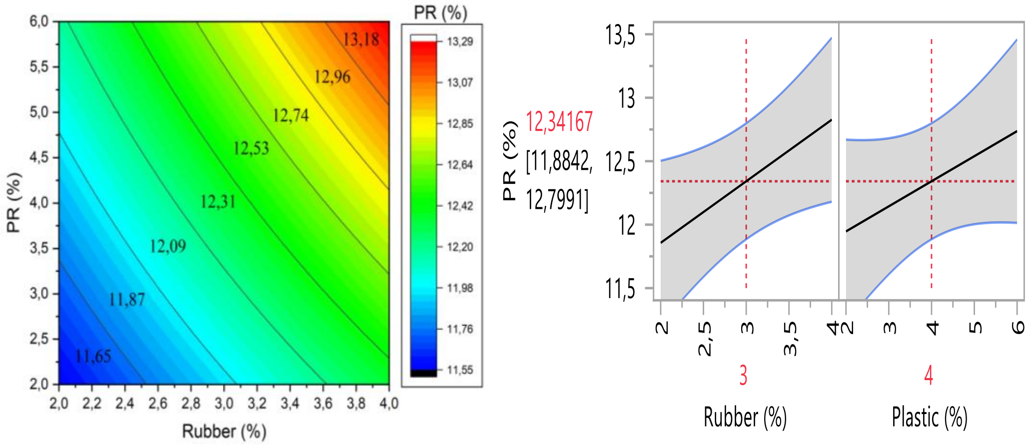
Figure 8: (a) Isoresponse curves and (b) Main effect plots of ultrasonic pulse velocity

3.3.3 Porosity (PR)

Figure 9, shows the iso-response curve and main plots of the porosity. The porosity increases from 11.75% to 13.5% when increasing the level of rubber from 2% to 4% and plastic from 2% to 6%. It also recorded high porosity levels when the rubber content ranged from 3.2% to 4% and the plastic content ranged from 4% to 6%. This indicates that specific ranges of rubber and plastic content in the mixture can result in even greater porosity levels. The introduction of rubber and plastic into the concrete mixture contributed to the increase in porosity by creating small voids or bubbles within the concrete. These voids or bubbles act as spaces within the concrete that increase its overall porosity, allowing for higher levels of air to pass through the concrete. These results are in agreement with those obtained by some authors [17, 39]. Eq. 3 represents the porosity mathematical model.

$$PR\ (\%) = 12.34 + 0.48\ (Rubber-3) + 0.39\ \left(\frac{Plastic-4}{2}\right) + (Rubber-3)\ \left(\frac{Plastic-4}{2}\right)(0.09) \quad (3)$$

The coefficients of rubber and plastic are (0.48) and (0.39), respectively, which shows that the effect of rubber and plastic is positive on the response.



(a) (b)

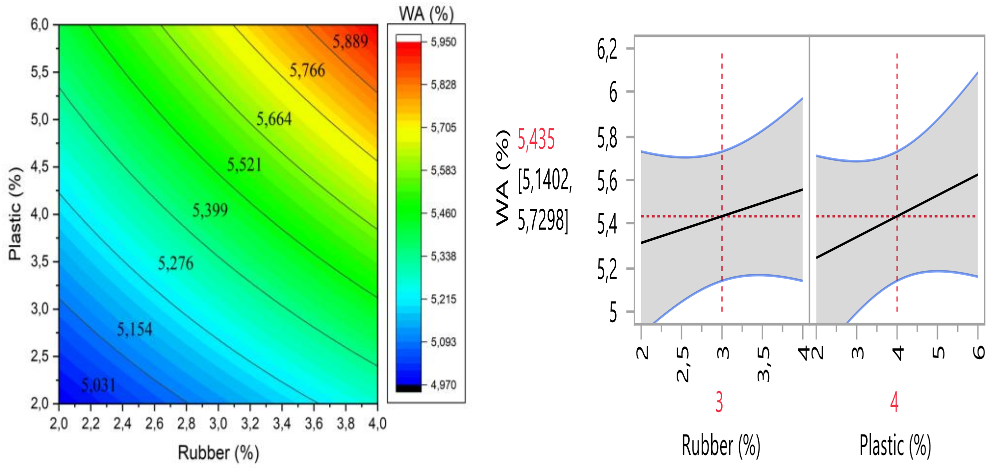
Figure 9: (a) Isoresponse curves and (b) Main effect plots of porosity

3.3.4 Water absorption by total immersion (WA)

Figure 10, shows the iso-response curve and main effect of water absorption by total immersion. Water absorption increases with increasing levels of rubber and plastic. The water absorption increases, reaching a maximum of 13.44% in concrete containing 4% rubber and 6% plastic. Rubber and plastic in the concrete mix can create interfaces with the cement matrix, potentially leading to the formation of holes or voids within the concrete. These voids can act as channels for water to seep into the concrete, ultimately increasing the water absorption in the concrete. These results are in agreement with those obtained by some authors [17, 30, 31, 40]. Eq. 4 represents the porosity mathematical model.

$$WA\ (\%) = 5.43+0.12\ (Rubber-3) +0.19\ \left(\frac{Plastic-4}{2}\right) + (Rubber-3)\ \left(\frac{Plastic-4}{2}\right)(0.34) \quad (4)$$

The coefficients of rubber and plastic are (0.12) and (0.19), respectively, which shows that the effect of rubber and plastic is positive on the response.



(a) (b)

Figure 10: (a) Isoresponse curves and (b) Main effect plots of the total immersion water absorption

3.3.5 Water absorption by capillary (WAC)

Figure 11 (a) and (b), show the iso-response and main effect plots of water absorption by capillary. It was seen that as the level of rubber and plastic increased, the water absorption by capillary increased. The mixture of 4% rubber and 6% plastic registered a high water absorption by capillary of 49% as compared to ordinary concrete. It was observed that the rubber and plastic had a positive effect on water absorption by capillaries. This increase can be attributed to the fact that plastic and rubber do not bond with concrete components, so plastic and rubber create voids in the concrete mix. These additional voids allow water to penetrate the concrete more easily, so water absorption by capillary action increases. These results are in agreement with those obtained by some authors [22–33].The mathematical model of water absorption by capillaries is written in Eq.5.

$$WAC\ (g/m^2) = 11.28 + 1.17\ (Rubber\text{-}3) + 0.69\ \left(\frac{Plastic-4}{2}\right) + (Rubber\text{-}3)\ \left(\frac{Plastic-4}{2}\right)(0.51) \qquad (5)$$

The coefficients of the rubber and the plastic, are (1.17), and (0.69), respectively. As well the effect of rubber is tow times greater than effect of plastic on the water absorption by capillary.

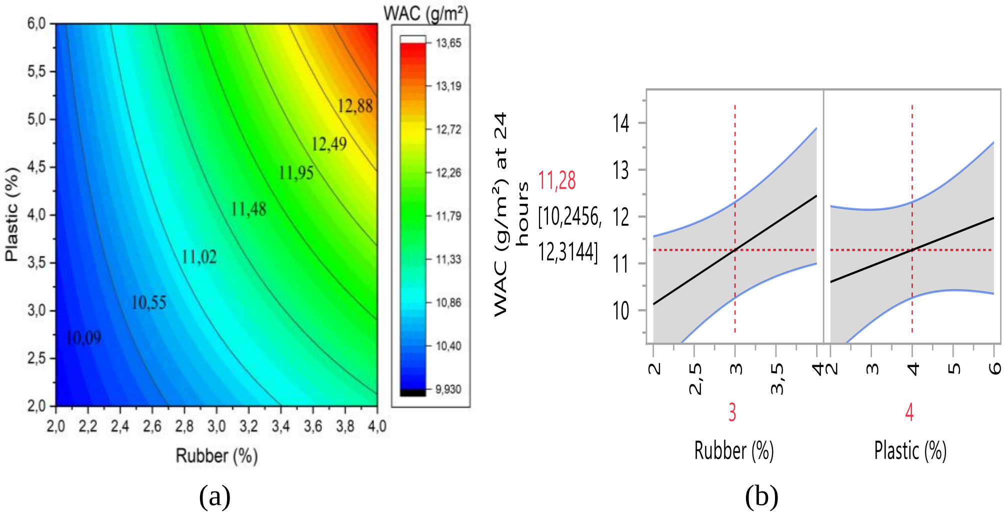


Figure 11: (a) Isoresponse curves and (b) Main effect plots of the total immersion water absorption by capillary

3.3.6 Coefficient Estimates

From Tables 8, 9, 10, and 11 estimating the response coefficients, it is quite clear that the rubber effect is the most influential on the ultrasonic pulse velocity, porosity, and capillary water absorption; they have the lowest value of (prob.>|t|). Except for water absorption by complete immersion, the interaction between rubber and plastic is the factor that most affects it.

Table 8: Coefficient Estimates of UPV

Term	Estimate	Standard Error	t ratio	Prob. > |t|
Rubber (%) (2,4)	-58.29167	4.110983	-14.18	0.0049*
Plastic (%)(2,6)	-54.59	5.034905	-10.84	0.0084*
Rubber (%) *Plastic (%)	5.535	5.034905	1.10	0.3863

Table 9: Coefficient Estimates of PR

Term	Estimate	Standard Error	t ratio	Prob. > |t|
Rubber (%) (2,4)	0.485	0.106315	4.56	0.0448*
Plastic (%)(2,6)	0.395	0.130208	3.03	0.0936
Rubber(%)*Plastic (%)	0.09	0.130208	0.69	0.5609

Table 10: Coefficient Estimates of WA

Term	Estimate	Standard Error	t ratio	Prob. > |t|
Rubber (%) *Plastic (%)	0.34	0.083915	4.05	0.0559
Plastic (%)(2,6)	0.19	0.083915	2.26	0.1518
Rubber (%) (2,4)	0.1216667	0.068516	1.78	0.2178

Table 11: Coefficient Estimates of WAC

Term	Estimate	Standard Error	t ratio	Prob. > |t|
Rubber (%) (2,4)	1.17	0.240416	4.87	0.0397*
Plastic (%)(2,6)	0.69	0.294449	2.34	0.1438
Rubber (%) *Plastic (%)	0.51	0.294449	1.73	0.2254

3.4 Microstructural analysis

According to the SEM images in Figures 12 and 13, ordinary concrete contains fewer air bubbles, while the rubber and plastic particles in the concrete lead to the formation of larger air bubbles inside the concrete structure. These results are in agreement with those obtained by some authors [41]. When rubber and plastic are mixed with concrete, they do not bond properly with the cement paste, leading to the formation of voids and cracks as the concrete cures, as shown in Figure 14. These voids and cracks can increase the porosity of the concrete, which increases the rate of water absorption, as shown in Figures 9, and 10.

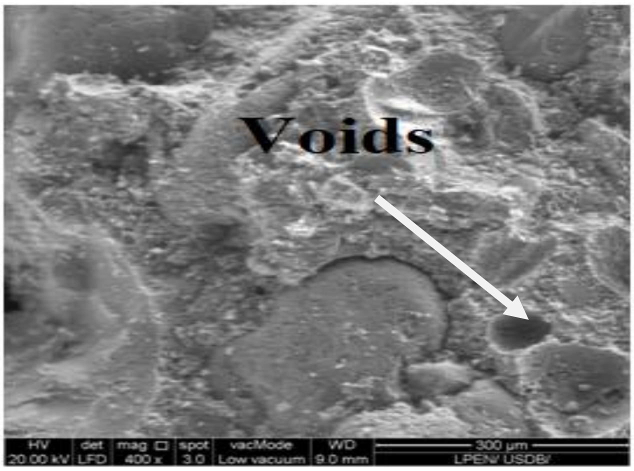


Figure 12: SEM image of ordinary concrete (x400)

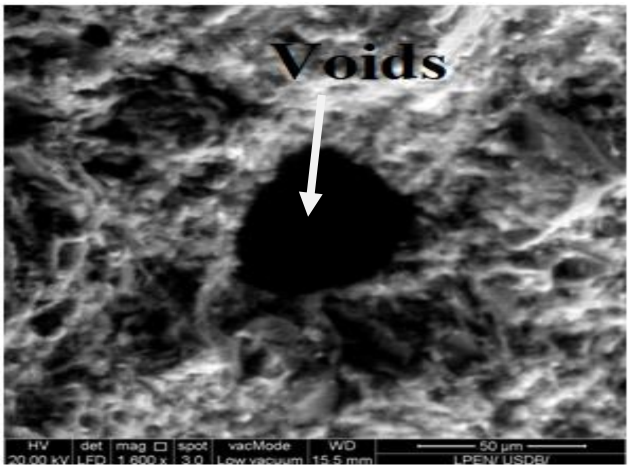


Figure 13: SEM image of concrete containing 4% rubber and 6%plastic (x1600)

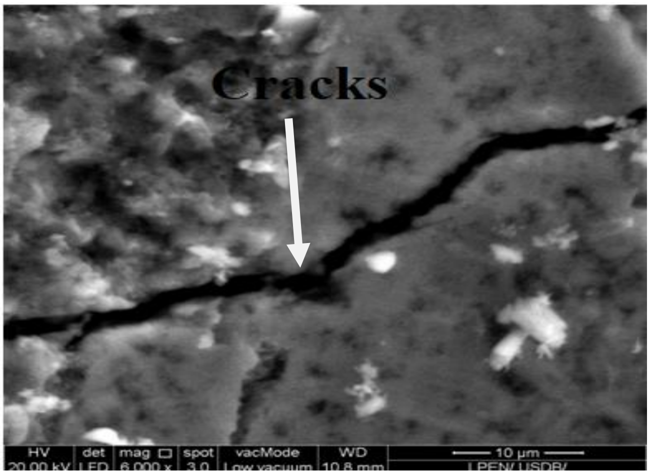


Figure 14: SEM of concrete containing 4% rubber and 6% plastic (x6000)

3.5. Image J analysis

In this study, SEM images of conventional concrete and concrete blended with residual rubber and plastic materials are examined using Image J software.
The area occupied by the pores for concrete samples can be found by analysis using image J [42], a public domain Java image processing program.
The results for the concrete samples are shown in Figures 15, and 16 and the results for the pores area of the various specimens are obtained in Table 12.
These findings showed that the percentage of pores in ordinary concrete was lower than that of concrete with plastic and rubber in it. In ordinary concrete (BO), the percentage of pores is 2.862%, and in concrete with 4% rubber and 6% plastic (B6), the percentage of pores is 6.502%. Because plastic and rubber are non-adherent, they can create cavities in concrete. These substances might not properly bind with the surrounding cementitious material when added to fresh concrete, which would increase the percentage of porosity in the concrete.

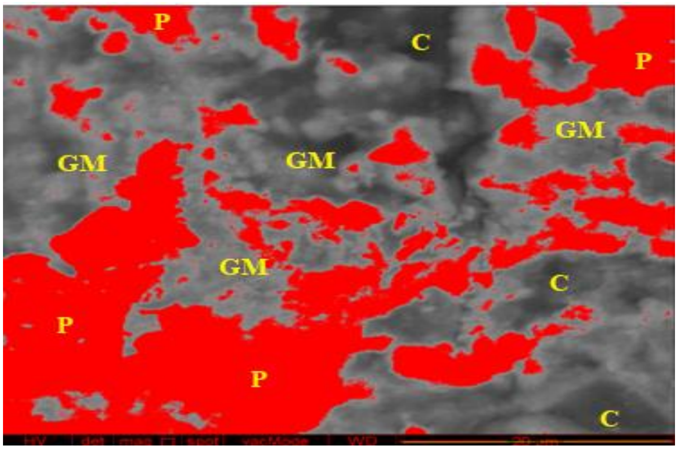


Figure 15: SEM images showing the BO after Image J analysis (GM: granular material, sand/gravel; P: pore; C: cement)

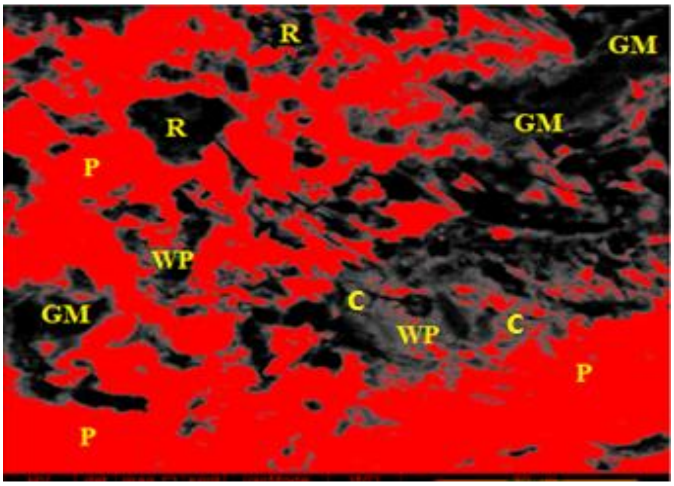


Figure 16: SEM images showing the B6 after Image J analysis (GM: granular material, sand/gravel; P: pore; C: cement; R: rubber; WP: plastic)

Table 12: % Pores area of BO and B6 from image J analysis

Specimen	% pores area
BO	2.862
B6	6.502

4 Conclusion

The experimental results and numerical modeling of the use of waste rubber and plastic in concrete allowed us to draw the full conclusions:

- The ultrasonic pulse velocity and porosity had a strong association relationship with a coefficient of R^2= 0.90.
- Porosity and water absorption have a correlation coefficient of R^2 = 0.67, and porosity increases lead to higher water absorption.
- The increase in the level of rubber and plastic causes a decrease in the ultrasonic pulse velocity of the concrete. The mixture of 4% rubber and 6% plastic registers a low ultrasonic pulse velocity of 6.33% as compared to ordinary concrete.
- Concrete with waste plastic and rubber shows increases in porosity, water absorption by total immersion, and water absorption by capillary; a mixture of 4% rubber and 6% plastic recorded high values for these parameters, registering 26.43%, 38.73%, and 49.30%, respectively, compared to ordinary concrete.
- Statistical parameters show good correlation coefficients (R^2= 0.99; 0.93; 0.92; and 0.94) for ultrasonic pulse velocity, porosity, water absorption by total immersion, and water absorption by capillary, respectively.
- From estimating the coefficients of the response, it was observed that the influence of rubber has the most effect on these responses.
- Adding rubber and plastic aggregates to concrete leads to the formation of larger air bubbles within the structure compared to regular concrete, as revealed by SEM and Image J analysis. This difference is because plastic and rubber aggregates do not adhere to the concrete components, resulting in increased air bubble size.

This study provides valuable information about the reuse of this waste in the field of civil engineering. By incorporating these waste materials into concrete production, we can not only reduce waste but also create lightweight, soundproof concrete solutions. This has the potential to have a positive impact on the environment and improve sustainability in building practices.

Acknowledgments

The auteurs express their great gratitude to the University of SKIKDA in Algeria.

References

[1] Aziz, P L., & Abdulkadir, M. R. (2022). Mechanical Properties and Flexural Strength of Reinforced Concrete Beams Containing Waste Material as Partial Replacement for Coarse Aggregates. *International Journal of Concrete Structures and Materials*, *16*(1).

[2] Daghistani, F., Baghbani, A., Naga, H. A., & Faradonbeh, R. S. (2023). Internal Friction Angle of Cohesionless Binary Mixture Sand–Granular Rubber Using Experimental Study and Machine Learning. *Geosciences*, *13*, 7–197. https://doi.org/10.3390/geosciences13070197

[3] Meles, D., Bayat, A., & Chan, D. (2013). One-dimensional compression model for tire-derived aggregate using large-scale testing apparatus. *International Journal of Geotechnical Engineering*, *8*(2), 197–204. https://doi.org/10.1179/1939787913y.0000000019

[4] Rouhanifar, S., & Ibraim, E. (2015). *Laboratory investigation on the mechanics of soft-rigid soil mixtures*. 1073–1080. https://doi.org/10.3233/978-1-61499-601-9-1073

[5] Lamba, P., Kaur, D. P., Raj, S., & Sorout, J. (2021). Recycling/reuse of plastic waste as construction material for sustainable development: a review. *Environmental Science and Pollution Research International*, *29*(57), 86156–86179. https://doi.org/10.1007/s11356-021-16980-y

[6] Mansouri, I., Safa, M., Ibrahim, Z., Kisi, O., Tahir, M., Baharom, S., & Azimi, M. (2016). Strength prediction of rotary brace damper using MLR and MARS. *STRUCTURAL ENGINEERING AND MECHANICS*, *60*(3), 471–488. https://doi.org/10.12989/sem.2016.60.3.471

[7] Kou, S., Lee, G., Poon, C., & Lai, W. (2009). Properties of lightweight aggregate concrete prepared with PVC granules derived from scraped PVC pipes. *Waste Management*, *29(2)*, 621–628. https://doi.org/10.1016/j.wasman.2008.06.014

[8] Senhadji, Y., Escadeillas, G., Benosman, A., Mouli, M., Khelafi, H., & Ould Kaci, S. (2015). Effect of incorporating PVC waste as aggregate on the physical, mechanical, and chloride ion penetration behavior of concrete. *Journal of Adhesion Science and Technology, 29(7),* 625–640. https://doi.org/10.1080/01694243.2014.1000773

[9] Haghighatnejad, N., Mousavi, S. Y., Khaleghi, S. J., Tabarsa, A., & Yousefi, S. (2016). Properties of recycled PVC aggregate concrete under different curing conditions. *Construction and Building Materials, 126,* 943–950. https://doi.org/10.1016/j.conbuildmat.2016.09.047

[10] Gesoglu, M., Güneyisi, E., Hansu, O., Etli, S., & Alhassan, M. (2017). Mechanical and fracture characteristics of self-compacting concretes containing different percentage of plastic waste powder. *Construction and Building Materials, 140,* 562–569. 140, 562–569. https://doi.org/10.1016/j.conbuildmat.2017.02.139

[11] Najjar, A.M. K., Basha, E. A., & Bashaand, Milad, M.B.K. (2013). Rigid polyvinyl chloride waste for partial replacement of natural coarse aggregate in concrete mixture. *Int. J. Chem. Environ. Eng, 4 (6)* 399–403.

[12] Aly, A. M., El-Feky, M., Kohail, M., & Nasr, E. S. A. (2019). Performance of geopolymer concrete containing recycled rubber. *Construction and Building Materials, 207,* 136–144. https://doi.org/10.1016/j.conbuildmat.2019.02.121

[13] Guo, S., Dai, Q., Si, R., Sun, X., & Lu, C. (2017). Evaluation of properties and performance of rubber-modified concrete for recycling of waste scrap tire. *Journal of Cleaner Production, 148,* 681–689. https://doi.org/10.1016/j.jclepro.2017.02.046

[14] Senhadji, Y., Escadeillas, G., Benosman, A., Mouli, M., Khelafi, H., & Ould Kaci, S. (2015). Effect of incorporating PVC waste as aggregate on the physical, mechanical, and chloride ion penetration behavior of concrete. *Journal of Adhesion Science and Technology, 29(7),* 625–640. https://doi.org/10.1080/01694243.2014.1000773

[15] Akçaözoğlu, S., Atiş, C. D., & Akçaözoğlu, K. (2010). An investigation on the use of shredded waste PET bottles as aggregate in lightweight concrete. *Waste Management, 30(2),* 285–290. https://doi.org/10.1016/j.wasman.2009.09.033

[16] Saikia, N., & de Brito, J. (2012). Use of plastic waste as aggregate in cement mortar and concrete preparation: A review. *Construction and Building Materials, 34,* 385–401. https://doi.org/10.1016/j.conbuildmat.2012.02.066

[17] Colangelo, F., Cioffi, R., Liguori, B., & Iucolano, F. (2016). Recycled polyolefins waste as aggregates for lightweight concrete. *Composites. Part B, Engineering*, *106*, 234–241. https://doi.org/10.1016/j.compositesb.2016.09.041

[18] Coppola, B., Courard, L., Michel, F., Incarnato, L., Scarfato, P., & Di Maio, L. (2018). Hygro-thermal and durability properties of a lightweight mortar made with foamed plastic waste aggregates. *Construction and Building Materials, 170,* 200–206. https://doi.org/10.1016/j.conbuildmat.2018.03.083

[19] Albano, C., Camacho, N., Hernandez, M., Matheus, A., & Gutiérrez, A. (2009). Influence of content and particle size of waste pet bottles on concrete behavior at different w/c ratios. *Waste Management, 29(10),* 2707–2716. https://doi.org/10.1016/.wasmaan.2009.05.007

[20] Kou, S., Lee, G., Poon, C., & Lai, W. (2009). Properties of lightweight aggregate concrete prepared with PVC granules derived from scraped PVC pipes. *Waste Management*, *29(2)*, 621–628. https://doi.org/10.1016/j.wasman.2008.06.014

[21] Senthil Kumar, K., Gandhimathi, R., & Baskar, K. (2016). Assessment of Heavy Metals in Leachate of Concrete Made With E-Waste Plastic. *Advances in Civil Engineering Materials, 5(1),* 256–262. https://doi.org/10.1520/acem20160003

[22] Chidiac, S., & Mihaljevic, S. (2011). Performance of dry cast concrete blocks containing waste glass powder or polyethylene aggregates. *Cement and Concrete Composites*, *33(8),* 855–863. https://doi.org/10.1016/j.cemconcomp.2011.05.004

[23] Kumar, R., & Dev, N. (2021). Mechanical and Microstructural Properties of Rubberized Concrete After Surface Modification of Waste Tire Rubber Crumb. *Arabian Journal for Science and Engineering*, *47(4),* 4571–4587. https://doi.org/10.1007/s13369-021-06154-w

[24] Djebien, R., Bouabaz, A., & Abbas, Y. (2022). Effect of Recycled Tire Rubber and Marble Waste on Fresh and Hardened Properties of Concrete. *Civil and Environmental Engineering Reports*, *32*(1), 218–239. https://doi.org/10.2478/ceer-2022-0013

[25] Si, R., Wang, J., Guo, S., Dai, Q., & Han, S. (2018). Evaluation of laboratory performance of self-consolidating concrete with recycled tire rubber. *Journal of Cleaner Production, 180,* 823–831. https://doi.org/10.1016/j.jclepro.2018.01.180

[26] Ramdani, S., Guettala, A., Benmalek, M., & Aguiar, J. B. (2019). Physical and mechanical performance of concrete made with waste rubber aggregate, glass powder and silica sand powder. *Journal of Building Engineering, 21,* 302–311. https://doi.org/10.1016/j.jobe.2018.11.003

[27] Khan Raja, Bilal Nasar., & Khitab, Anwar. (2020). Enhancing Physical, Mechanical and Thermal Properties of Rubberized Concrete. *In: Engineering and Technology Quarterly Reviews, Vol.3, No.1,* 33-45. https://www.asianinstituteofresearch.org/

[28] Uratsinze, A., & Garros, M. (2008). On the modulus of elasticity and strain capacity of Self-Compacting Concrete incorporating rubber aggregates. *Resources, Conservation and Recycling, 52(10),* 1209–1215. https://doi.org/10.1016/j.resconrec.2008.06.012

[29] Gupta, T., Chaudhary, S., & Sharma, R. K. (2014). Assessment of mechanical and durability properties of concrete containing waste rubber tire as fine aggregate. *Construction and Building Materials, 73,* 562–574. https://doi.org/10.1016/j.conbuildmat.2014.09.102

[30] Yilmaz, A., & Degirmenci, N. (2009). Possibility of using waste tire rubber and fly ash with Portland cement as construction materials. *Waste Management, 29(5),* 1541–1546. https://doi.org/10.1016/j.wasman.2008.11.002

[31] Ganjian, E., Khorami, M., & Maghsoudi, A. A. (2009). Scrap-tyre-rubber replacement for aggregate and filler in concrete. *Construction and Building Materials, 23(5),* 1828–1836. https://doi.org/10.1016/j.conbuildmat.2008.09.020

[32] Thomas, B. S., & Gupta, R. C. (2016). A comprehensive review on the applications of waste tire rubber in cement concrete. *Renewable & Sustainable Energy Reviews, 54,* 1323–1333. https://doi.org/10.1016/j.rser.2015.10.092

[33] Thomas, B. S., Gupta, R. C., Kalla, P., & Cseteneyi, L. (2014). Strength, abrasion and permeation characteristics of cement concrete containing discarded rubber fine aggregates. *Construction and Building Materials, 59,* 204–212. https://doi.org/10.1016/j.conbuildmat.2014.01.074

[34] Azimi-Pour, M., & Eskandari-Naddaf, H. (2020). Synergistic effect of colloidal nano and micro-silica on the microstructure and mechanical properties of mortar using full factorial design. *Construction and Building Materials, 261,* 120497. https://doi.org/10.1016/j.conbuildmat.2020.120497

[35] Mutuk, T., & Mesci, B. (2014). Analysis of mechanical properties of cement containing boron waste and rice husk ash using full factorial design. *Journal of Cleaner Production, 69,* 128–132. https://doi.org/10.1016/j.jclepro.2014.01.051

[36] Belmouhoub, A., Abdelouahed, A., & Noui, A. (2023). Experimental and factorial design of the mechanical and physical properties of concrete containing waste rubber powder. *Research on Engineering Structures and Materials*. https://doi.org/10.17515/resm2023.54me0810rs

[37] Najim, K. B., & Hall, M. R. (2012). Mechanical and dynamic properties of self-compacting crumb rubber modified concrete. *Construction and Building Materials, 27(1),* 521–530. https://doi.org/10.1016/j.conbuildmat.2011.07.013

[38] Belmokaddem, M., Mahi, A., Senhadji, Y., & Pekmezci, B. Y. (2020). Mechanical and physical properties and morphology of concrete containing plastic waste as aggregate. *Construction and Building Materials, 257,* 119559. https://doi.org/10.1016/j.conbuildmat.2020.119559

[39] Hannawi, K., Kamali-Bernard, S., & Prince, W. (2010). Physical and mechanical properties of mortars containing PET and PC waste aggregates. *Waste Management, 30(11),* 2312–2320. https://doi.org/10.1016/j.wasman.2010.03.028

[40] Silva, R., de Brito, J., & Saikia, N. (2013). Influence of curing conditions on the durability-related performance of concrete made with selected plastic waste aggregates. *Cement and Concrete Composites, 35(1),* 23–31. https://doi.org/10.1016/j.cemconcomp.2012.08.017

[41] Gupta, T., Siddique, S., Sharma, R. K., & Chaudhary, S. (2021). Investigating mechanical properties and durability of concrete containing recycled rubber ash and fibers. *Journal of Material Cycles and Waste Management, 23(3),* 1048–1057. https://doi.org/10.1007/s10163-021-01192-w

[42] Nanes, B. A. (2015). Slide Set: Reproducible image analysis and batch processing with ImageJ. *BioTechniques, 59(5),* 269–278. https://doi.org/10.2144/0001