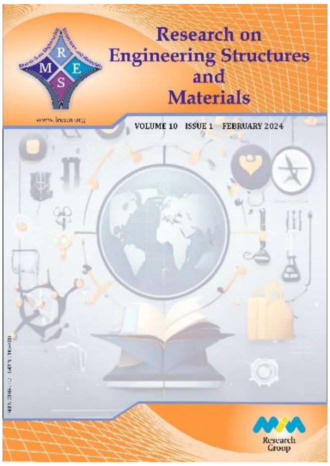
Research on Engineering Structures & Materials
www.jresm.org
Research Group




# Experimental and factorial design of the mechanical and physical properties of concrete containing waste rubber powder

Ameur Belmouhoub, Assia Abdelouahed, Ammar Noui

Online Publication Date: 20 October 2023
URL: http://www.jresm.org/archive/resm2023.54me0810rs.html
DOI: http://dx.doi.org/10.17515/resm2023.54me0810rs

Journal Abbreviation: *Res. Eng. Struct. Mater.*

**To cite this article**
Belmouhoub A, Abdelouahed A, Noui A. Experimental and factorial design of the mechanical and physical properties of concrete containing waste rubber powder. *Res. Eng. Struct. Mater.*, 2024; 10(2): 461-480.

Research on Engineering Structures & Materials
www.jresm.org
MIM Research Group

*Research Article*

# Experimental and factorial design of the mechanical and physical properties of concrete containing waste rubber powder

Ameur Belmouhoub[*1, a], Assia Abdelouahed[1, b], Ammar Noui[2, c]

[1]*Dept. of Civil Eng., 20 Août 1955 University of Skikda, Algeria*
[2]*Dept. of Civil Eng., Mohamed El Bachir El Ibrahimi University of Bordj Bou Arreridj, Algeria*

**Article Info**

*Article history:*

Received 10 Aug 2023
Accepted 20 Oct 2023

*Keywords:*

*Rubber;*
*Mechanical and physical properties;*
*Performance;*
*Substitution;*
*Full factorial design;*
*Waste*

**Abstract**

The application of waste rubber in the Civil Engineering is considered one of the most effective solutions for managing this waste. Therefore, the aim of this study is to analyze the effect of rubber substituted in cement on the physical and mechanical properties of concrete using the general full factorial design method, and compare the laboratory results with the results of the JMP pilot test program, and find out if there is a match between the results. The rubber powder is used as a mass substitute in cement at rates of 0%, 2%, 4%, 6% and 8%. The fresh properties were evaluated through workability, air content, and fresh density tests, whereas the hardened properties were assessed using tests of compressive strength, flexural strength, and ultrasonic pulse velocity. These concretes have the workability from 8 to 14.5 cm, fresh density from 2.20 to 2.38 (g/cm$^3$). The air content ranged from 1.2 to 1.9%. Furthermore, the compressive strength ranged from 22.85 to 43.97 MPa, while the flexural strength ranged from 4.86 to 7.03 MPa. In addition, ultrasonic velocity from 3831.42 to 4098.36 (m/s). Accordingly, it was concluded that the concrete with 2% of rubber represented significantly better compressive strength compared to the ordinary concrete. The numerical modeling is assessed to have an appropriate determined coefficient $R^2$ close to 1 for the workability, fresh density, air content, compressive strength, flexural strength, and ultrasonic pulse velocity.



## 1. Introduction

The exponential rise in population and transportation growth is increasing the tire manufacturing for automobiles [1]. Waste tires that are no longer in use produce a significant amount of rubber waste. In 2017, the production of tires in the world exceeded 2.9 billion tires per year [2]. By 2030, 1200 million more motor vehicle tires are predicted to be produced with 5000 million of those destined for landfills [3]. The accumulation of waste rubber tires has negative effects on the environment and human health [4]. Rubber is not biodegradable, and its combustion produces toxic gases that are harmful to humans [5]. Additionally, the aggregation of waste rubber provides an ideal environment for the breeding of dangerous insects that could cause significant illnesses among people [6]. Researchers attempted to provide an appropriate guideline for recycling waste materials in a way that protects the environment and contributes to economic growth. 46% of this rubber waste was used as fuel for generating energy, while 36% of it was buried, and 21% was used in the field of civil engineering. Researchers investigated the impact of recycled rubber on the properties of concrete and discovered that it offers one of the most effective means to eliminate this waste, recycled rubber was utilized as modifiers or additives in

*Corresponding author: a.belmouhoub@univ-skikda.dz
[a] orcid.org/0009-0002-9468-8717; [b] orcid.org/0000-0001-5671-7033; [c] orcid.org/0009-0005-6325-7131
DOI: http://dx.doi.org/10.17515/resm2023.54me0810rs

Portland Cement Concrete (PCC) combinations and asphalt paving mixtures [7]. Accordingly, Maher Al-Tayeb et al. [8] employed rubber powder with a content of 2.5%, 5%, and 10% substituted in cement. They found that the workability increased with increasing the percentage of rubber. As well, the compressive strength decreased by 19%, 32%, and 53% for concrete containing 2.5%, 5%, and 10% rubber, respectively. Wang et al. [9] demonstrated an increase in workability with an increase in the percentage of rubber. In addition, Steyn et al. [10] used three types of waste (low-density polyethylene plastic, rubber, and glass) in proportions of 15% and 30% as a substitution in fine aggregates. The results obtained show that rubber and glass increase air content. Pelisser et al. [11] report that rubberized concrete has a reported 13% lower density than ordinary concrete. Gupta et al. [12] register that replacing the natural fine aggregate by 20% with rubber ash results in a decrease in compressive strength and flexural strength of 28.77% and 32.87%, respectively. Singh et al. [13] used crumb rubber as a fine aggregate in concrete. They found the compressive strength decreased with increasing the amount of crumb rubber. The 15% replacement of crumb rubber as fine aggregates led to a 35% reduction in compressive strength as well as a decrease in ultrasonic pulse velocity compared to the reference concrete. Bisht and Ramana [14] used rubber powder in concrete at a ratio of 0%, 4%, 4.5%, 5%, and 5.5%. They observed that the flexural strength decreased by 2.9% and 16.5% for concrete containing 4% and 5.5% rubber powder, respectively. Pavankalyan et al. [15] used crumb rubber as a substitution for fine aggregates by 5% to 20%. The results obtained show that the compressive strength and ultrasonic pulse velocity decreased with increasing the percentage of rubber; the compressive strength decreased from 48 to 21.39 MPa for the mix CR0 and the mix CR20, respectively, compared to the reference concrete. In a study conducted by Najim and Hall [16], they replaced the fine and coarse aggregate, as well as a combination of both, with crumb rubber by 5% to 15%. The results indicated that the ultrasonic pulse velocity decreased as the amount of rubber replacement increased.

Table 1. Results of concrete with rubber obtained by the authors

| Authors | Substitution | Results |
|---|---|---|
| Maher Al-Tayeb et al. [8] and Wang et al. [9] | Rubber powder substitution in cement | Workability increased with an increase the rubber powder |
| Pelisser et al. [11] | Rubber used in concrete | Fresh density decreased by 13% compared to ordinary concrete |
| Chylík et al. [22] | Crumb rubber used in concrete | Air content increased with an increase the crumb rubber |
| Gupta et al. [12] | Replaced the fine aggregates by 20% with rubber ash | Compressive strength and flexural decreased by 28.77% and 32.87%, respectively |
| Singh et al. [13] | Used crumb rubber as fine aggregates in concrete | Compressive strength and ultrasonic pulse velocity decreased with an increase rubber |

Experiment design JMP is a statistical program that is used to plan and evaluate experiments that test scientific hypotheses, as well as to help users comprehend the findings and make well-informed decisions [17, 18]. The aim of this study is to analyze the effect of rubber substituted in cement on the physical and mechanical properties of concrete using the general full factorial design method, compare the laboratory results with the results of the JMP pilot test program, and find out if there is a match between the results.

## 2. Materials and Methods

### 2.1 Materials

In this work, six different types of materials are used to make the concrete: cement, rubber, sand (0/3), gravel (3/8), gravel (8/15), and water.

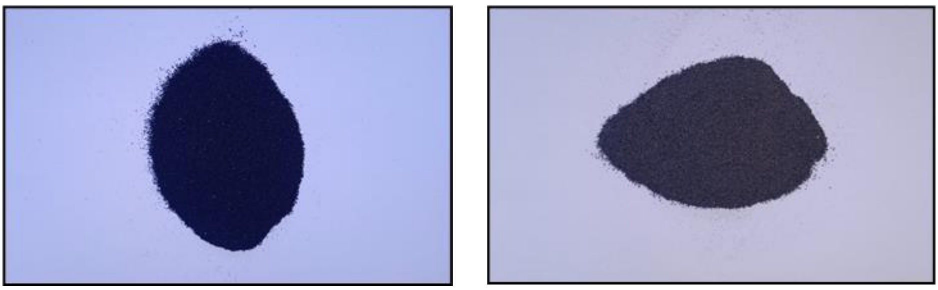
#### *2.1.1 Cement*

The cement used is of type CRS-CEMI-42.5 and was brought from the Ain Kebira Company, which is located in Setif, in the east of Algeria. The chemical properties, physical properties, and granulometric analyzer of this cement are stated in Table 2, Table 3, and Figure 3, respectively.

#### *2.1.2 Rubber*

The rubber waste used in this research is in the form of powder. It was brought from the El Hachimia plant, which is located in Bouira in the east of Algeria. The chemical properties, physical properties, and granulometric analyzer of this rubber are stated in Table 4, Table 5, and Figure 3, respectively.

The surface of the rubber is so smooth that it was treated with 10% NaOH and laid in this solution for 20 minutes. After extracting it from this solution, it is cleaned with water and then dried in the air. The aim of this treatment is to increase the adhesion of rubber to form a strong bond between rubber and cement, the figure 1 a) and b) present the rubber used in this research before and after treatment.



(a) (b)

Fig. 1. (a) Rubber before treatment, (b) rubber after treatment

#### *2.1.3 Sand*

The sand used in this research, sand of class 0/3, was brought from Oued Souf, situated in south Algeria. The physical properties, chemical properties, and granulometric analyzer of this sand are stated in Tables 5 and 6, respectively.

#### *2.1.4 Gravel*

The gravel used in this research gravel 3/8 and 8/15, was brought from the quarry Laala Aci-Mazara-Ain Lahdjar-Setif in the east of Algeria. The physical properties, chemical properties, and granulometric analyzer of this gravel are stated in Tables 5, 7, and 8, respectively.

*2.1.5 Water*

In this research, potable water was used in all the mixes.

Table 2. Chemical composition of the cement

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

Table 3. 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 |

Table 4. Chemical properties of the rubber

| Chemical components | Value (%) |
|---|---|
| Rubber hydrocarbon | 46.05 |
| Acetone extract | 15.20 |
| Inorganic sulfur | 0.60 |
| Ash content | 4.55 |
| Carbon black | 29.70 |
| $SiO_2$ | 0.55 |
| $TiO_2$ | 0.15 |
| ZnO | 1.70 |
| CaO | 0.55 |
| $Fe_2O_3 + Al_2O_3$ | 0.3 |
| Fiber content | 0.42 |
| Water content | 0.80 |

Table 5. Characteristics of sand (0/3), gravel (3/8), gravel (8/15), and rubber

| Characteristics | sand (0/3) | gravel (3/8) | gravel (8/15) | rubber |
|---|---|---|---|---|
| Absolute density (g /cm$^3$) | 2.55 | 2.66 | 2.66 | 0.94 |
| Apparent density (g/cm$^3$) | 1.62 | 1.36 | 1.42 | 0.34 |
| Fineness modulus (%) | 1.97 | / | / | / |
| Sand equivalent (%) | 81.61 | / | / | / |
| Absorption (%) | 2.5 | 0.99 | 0.99 | |

Table 6. Granulometric analyzer of sand (0/3

| Sand 0/3 | Cumulative refusal (g) | Cumulative refusal (%) | Passing (%) |
|---|---|---|---|
| 4 | 8 | 0.8 | 99.2 |
| 2 | 33 | 3.3 | 96.7 |
| 1 | 138 | 13.8 | 86.2 |
| 0.5 | 580 | 58 | 42 |
| 0.25 | 927 | 92.7 | 7.3 |
| 0.125 | 989 | 98.9 | 1.1 |
| 0.063 | 993 | 99.3 | 0.7 |
| Bottom | 993 | 99.3 | 0.7 |

Table 7. Granulometric analyzer of gravel (3/8)

| Gravel 3/8 | Cumulative refusal (g) | Cumulative refusal (%) | Passing (%) |
|---|---|---|---|
| 10 | 0 | 0 | 100 |
| 8 | 22 | 1.37 | 98.63 |
| 6.3 | 505 | 31.56 | 68.44 |
| 4 | 1488 | 93 | 7 |
| 2 | 1598 | 99.87 | 0.13 |
| Bottom | 1598 | 99.87 | 0.13 |

Table 8. Granulometric analyzer of gravel (8/15)

| Gravel 8/15 | Cumulative refusal (g) | Cumulative refusal (%) | Passing (%) |
|---|---|---|---|
| 16 | 15 | 0.5 | 99.5 |
| 12.5 | 589 | 19.63 | 80.37 |
| 10 | 1281 | 42.7 | 57.3 |
| 8 | 2410 | 80.33 | 19.67 |
| 6.3 | 2998 | 99.93 | 0.07 |
| Bottom | 2998 | 99.93 | 0.07 |

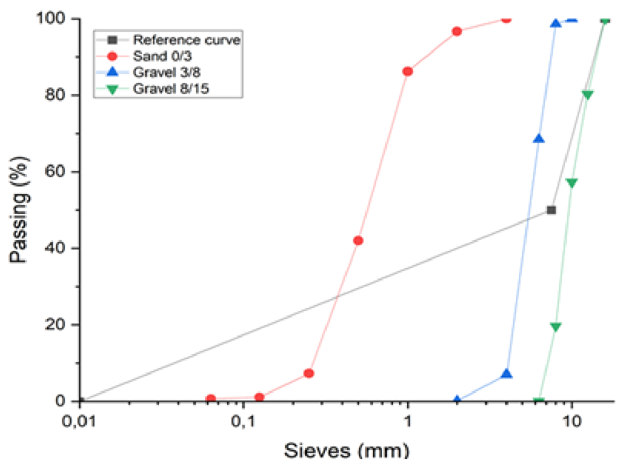



Fig. 2. Granulometric curve of the sand 0/3, gravel 3/8 and gravel 8/15

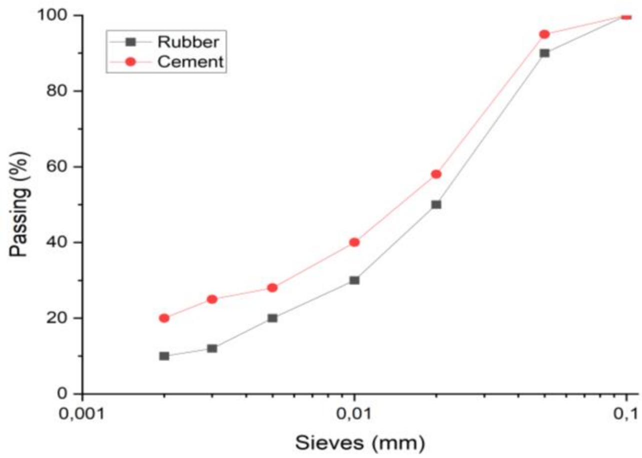



Fig. 3. Granulometric curve of the cement, and rubber

From Figure 2 and Figure 3, the particle size of sand, gravel 3/8, and gravel 8/15 was determined by a granulometric analyzer according to the NF EN 933-1 standard, and the particle size of cement and rubber was determined using a laser diffraction particle size analyzer according to the NF P 94-05792 standard.

### 2.2. Experimental Methods

In this work, the Dreux-Gorisse method is used. The Dreux-Gorisse method is an empirical method used to estimate the absolute density of concrete. It is based on the relationship between the absolute density of concrete and the absolute mass of its components (sand, gravel, cement, and water).

Table 9. 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$^3$) |
|---|---|---|---|---|---|---|
| 0 | 689 | 219 | 741 | 400 | 209 | 0 |
| 2 | 689 | 219 | 741 | 392 | 209 | 8 |
| 4 | 689 | 219 | 741 | 384 | 209 | 16 |
| 6 | 689 | 219 | 741 | 376 | 209 | 24 |
| 8 | 689 | 219 | 741 | 368 | 209 | 32 |

Table 10. The tests used with standards

| Tests | Standards |
|---|---|
| Workability | NF EN 12350-2 |
| Fresh density | NF EN 12350-6 |
| Air content | NF EN 12350-7 |
| Compressive strength | NF EN 12390-3 |
| Flexural strength | NF EN 12390-5 |
| Ultrasonic pulse velocity | NF EN 12504-4 |

Rubber powders were used to partially replace cement in the concrete at replacement weight ratios of 0, 2, 4, 6, and 8%. 0% of rubber powder was used as a reference, at every age, three pieces are used. The test specimens produced from the fresh concrete were stored for 24 hours in ambient laboratory conditions (20 °C). After 24 hours, the samples were removed from the molds. Subsequently, the test pieces were immersed in water until the time of the test. The molds used in these tests were 7 x 7 x 28 cm$^3$ and 10 x 10 x 10 cm$^3$.

## 4. Results

### 4.1. Fresh properties

This section displays three different types of tests: workability, fresh density, and air content.

#### *4.1.1. Workability*

The workability values of rubber concrete measured in the laboratory are presented in Figure 4. From figure 4, it can be seen that the workability increases when the amount of rubber increases. It was seen that the minimum value of the workability was 8 cm for control concrete (0% of rubber), and the highest value of the workability was 14.5 cm for concrete containing 8% rubber. The increase in workability was slight until the percentage of 6% of waste, where the increase was in rush.

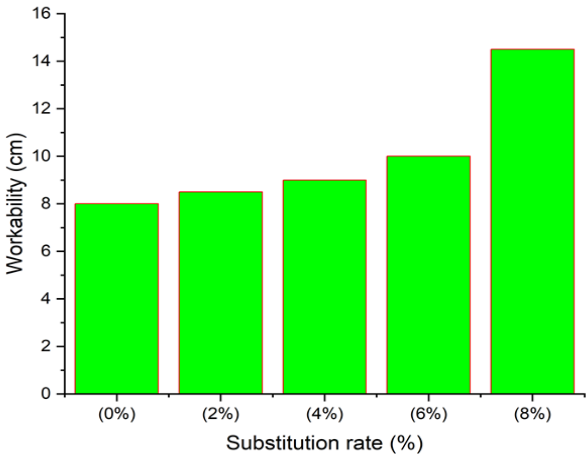



Fig. 4. Workability values with different rubber rations added to concrete

This increase in workability is due to the smooth surface of the rubber and its nature that does not absorb water, which makes the concrete more plastic, on the other hand, the presence of bulk water in the mixture. A similar result was given by [8, 9].

#### *4.1.2. Fresh Density*

The fresh density tests at rates of 0%, 2%, 4%, 6%, and 8% from the added rubber are presented in figure 5. The fresh density decreases as the ratio of rubber increases. The lowest density recorded is 2.20 g/cm$^3$ for concrete containing 8% of rubber, and the highest density is 2.38 g/cm$^3$ for concrete containing 0% of rubber. The incorporation of 2%, 4%, 6%, and 8% of rubber in concrete results in a decrease in fresh density of 2.10%, 2.94%, 5.46%, and 7.56%, respectively, as compared to ordinary concrete.

This drop is due to the fact that the density of rubber powder is much lighter compared to the density of natural aggregates (0.94 for rubber powder and 2.66 for natural aggregates). As well, the presence of rubber in cement and water can affect the hardening and cohesion processes of concrete, leading to the formation of voids in the concrete. This causes a decrease in density. These results are consistent with those obtained by some authors [19, 20].

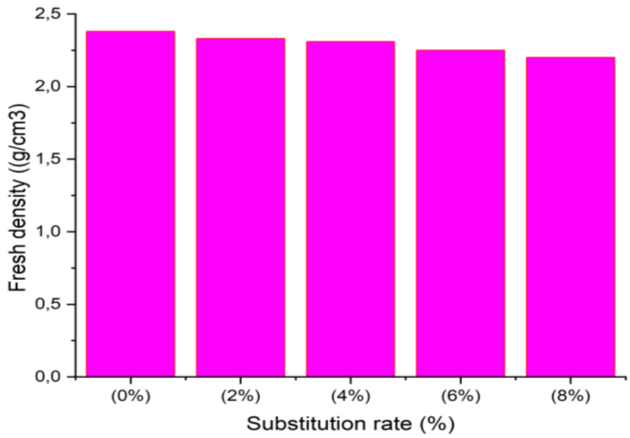



Fig. 5. Fresh density values with different rubber rations added to concrete

*4.1.3. Air Content*

The results of the air content test are presented in Figure 6. It has been observed from figure 6, that the air content increases with an increase in the percentage of rubber, and it was also found that the higher percentage of air content is 1.9% for concrete containing 8% rubber, which corresponds to an increase of 58% compared to normal concrete, and the low percentage of air content is 1.2% for concrete containing 0% rubber.

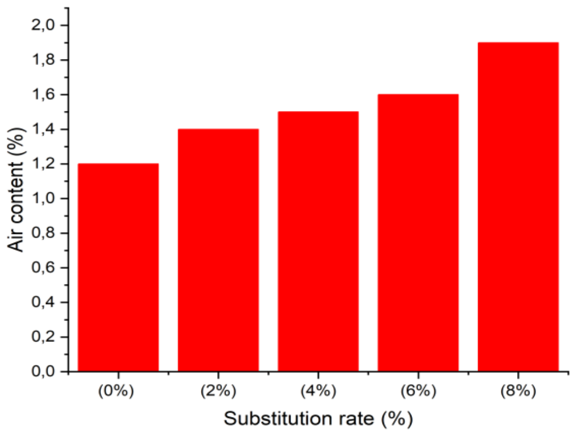



Fig. 6. Air content values with different rubber rations added to concrete

This increase is due to the low adhesion between the rubber powder and the cementitious matrix, which creates voids between the particles, so each time we increase the percentage of rubber, the air content increases, and on the other hand, the presence of rubber powder can create bubbles when mixed with concrete. These bubbles can trap air inside the concrete mass, increasing the amount of occluded air. These results are consistent with those obtained by some authors [21, 22].

### 4.2. Hardened Properties

In this section, three different sorts of tests are used: compressive strength, flexural strength, and ultrasonic pulse velocity.

*4.2.1. Compressive Strength*

The compressive strength of the samples was determined at the age of 28 days; the results are shown in Figure 7. It was seen that the maximum value of compressive strength is 43.97 MPa for concrete containing 2% rubber compared to ordinary concrete. After this value, the compressive strength continued to drop when increasing the percentage of rubber; the lowest recorded value is 22.85 MPa for concrete containing 8% rubber, which corresponds to a decrease of 47% compared to normal concrete. These results are consistent with those obtained by Abdullah et al. [23] found that the compressive strength for foamed concrete containing 6% and 9% of rubber continued to develop comparable to the reference concrete, except for the mixture, which contains 12% of rubber, whose resistance has decreased.

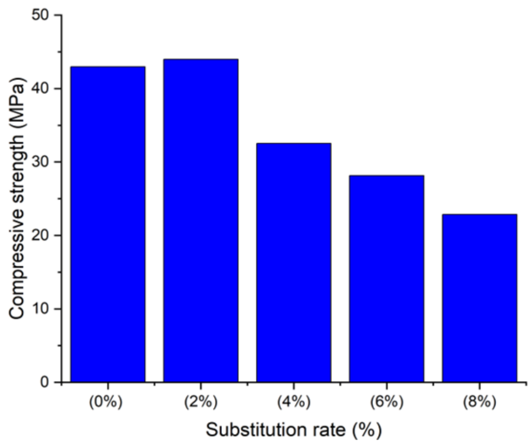



Fig. 7. Variation of compressive strength with different rubber rations added to concrete

This drop in compressive strength may be attributed to the low cohesion between the rubber granules and the cement, which creates voids in the mixture and leads to a decrease in compressive strength, and the poor hardness of rubber compared to natural aggregates. As well, rubber waste has a lower density than traditional aggregates, which means it can take up more space in the mixture. This can lead to a decrease in the amount of cement and aggregates in the mixture, which affects the compressive strength. These results are consistent with those obtained by [19, 22, 24].

*4.2.2. Flexural Strength*

The flexural strength of the samples was determined at the age of 28 days; the results are shown in Figure 8.

It was observed that the flexural strength at 28 days decreases when the percentage of rubber increases, the minimum value of flexural strength is 5 MPa for concrete containing 8% rubber, and the maximum value of flexural strength is 7.03 MPa for concrete containing 0% of rubber. Flexural strength decreases by up to 31% for concrete containing 8% rubber and decrease of 10% for concrete containing 2% rubber when compared to ordinary concrete. This decrease in flexural strength may be due to the same factors that caused a reduction in compressive strength. On the other hand, rubber has a strength that is lower than the strength of natural aggregate. These results are consistent with those obtained by [24, 25, 26].

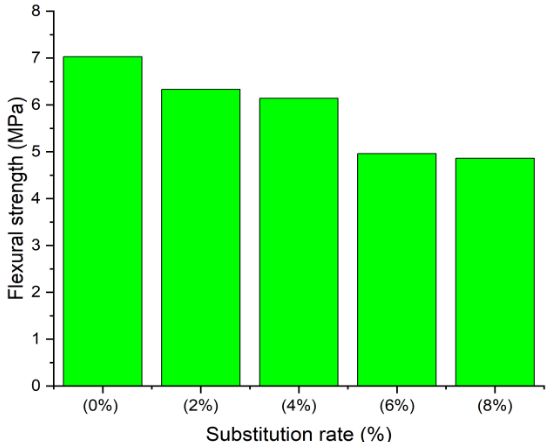



Fig. 8. Flexural strength of different concretes

*4.2.3. Ultrasonic pulse velocity*

Figure 9 shows the evolution of the ultrasonic pulse velocity of the concretes studied as a function of rubber substitution rates. Each time the percentage of rubber was increased, there was a drop in ultrasonic speed; the lowest value shown is 3831.42 m/s for concrete containing 8% of rubber.

The ultrasonic pulse velocity decreases by 2.24%, 3.55%, 4.31%, and 6.51% for concrete containing 2%, 4%, 6%, and 8% of rubber, respectively compared to the ordinary concrete. This drop in the speed of propagation of ultrasonic waves is explained by composites' higher levels of water and air content, which causes an increase in the time of ultrasonic propagation. Rubber waste present in concrete can create discontinuous interfaces or areas of low density, which can lead to a decrease in ultrasonic speed. This increase reduces the speed of propagation. These results are in agreement with those obtained by some authors [15, 27, 28].

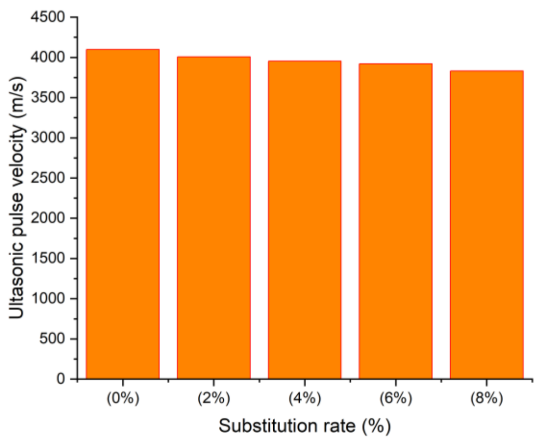



Fig. 9. Ultrasonic pulse velocity values with different rubber rations added to concrete

## 5. Modeling of The Physique and Mechanical Response

### 5.1 Statistical Study with Factorial Design Approach

An efficient statistical method for planning experimental research and assessing the primary and secondary effects between variables and independent effect variables is the factorial design [29, 30]. The anticipated result is taken from the mathematical equation shown below:

$$Y = X_0 + X_1 R \quad (1)$$

Where: (Y) is the expected response and ($X_0$, $X_1$,) are the model coefficients, and R is the rubber (%).

### 5.2 Correlation

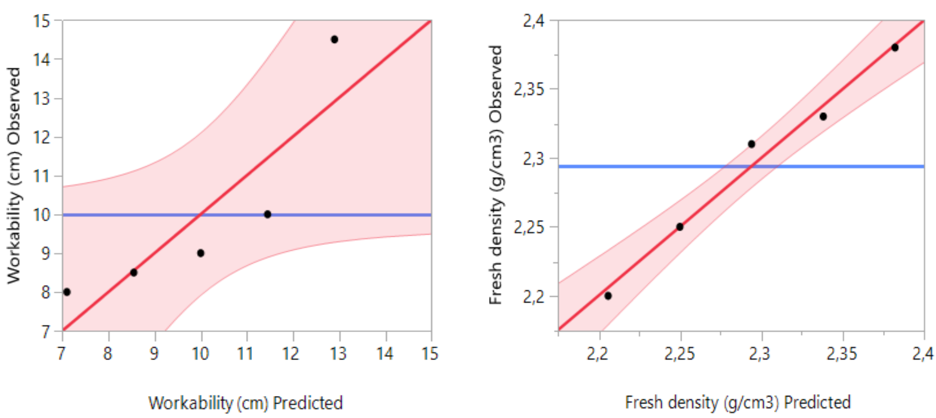
(Workability, Density, Air content, compressive strength, Flexural strength and ultrasonic pulse velocity). The results of the experimental tests presented in Table 11. We have five experiments proposed by full factorial design.

Table 11. Experimental results

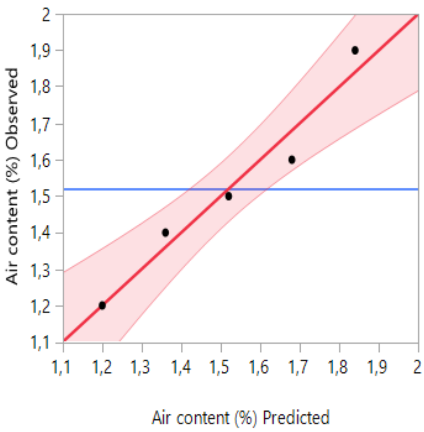
| Test | Rubber (%) | Workability (cm) | Density (kg/m³) | Air content (%) | Compressive strength (MPa) | Flexural strength (MPa) | Ultrasonic (m/s) |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 8 | 2.38 | 1.2 | 42.96 | 7.03 | 4098.36 |
| 2 | 2 | 8.5 | 2.33 | 1.4 | 43.97 | 6.33 | 4006.41 |
| 3 | 4 | 9 | 2.31 | 1.5 | 32.54 | 6.14 | 3952.57 |
| 4 | 6 | 10 | 2.25 | 1.6 | 28.15 | 4.96 | 3921.57 |
| 5 | 8 | 14.5 | 2.20 | 1.9 | 22.85 | 4.96 | 3831.42 |

### 5.3 Verification of the Proposed Models' Validity

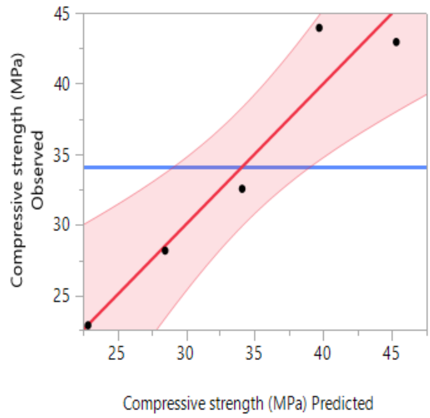
The correlation between the observed and predicted values is presented in Figure 10, and the experimental results of characterization tests are presented in Table 12. From figure 10, it can be seen that there is a high relationship between the results observed and the results predicted.



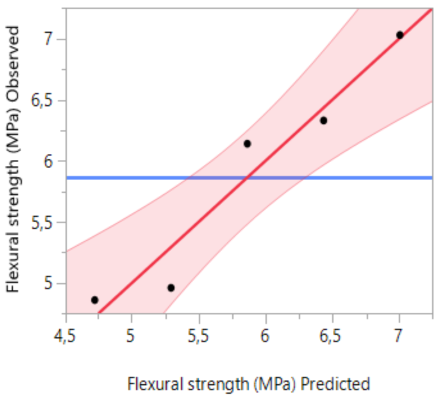

(a) Workability (b) Fresh density



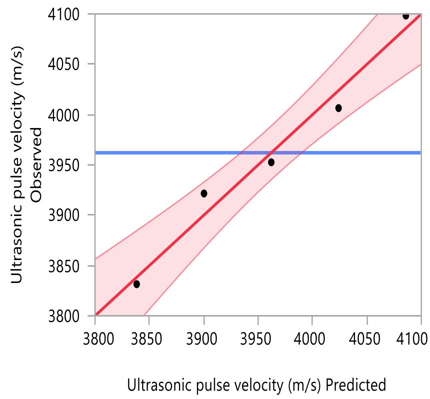

(c) Air content




(d) Compressive strength




(e) Flexural strength




(f) Ultrasonic pulse velocity

Fig. 10. Correlation between the observed and predicted responses a workability, fresh density, air content, compressive strength, flexural strength, and ultrasonic pulse velocity

It can be said that the applied models are very accurate in predicting the behavior of rubber in the physical and mechanical properties of concrete, and from Table 12. It can be observed that the correlation coefficients are between 0.76 and 0.97 and are close to 1, which indicates a good correlation between the predicted and experimental models.

Table 12. Experimental results of characterization tests

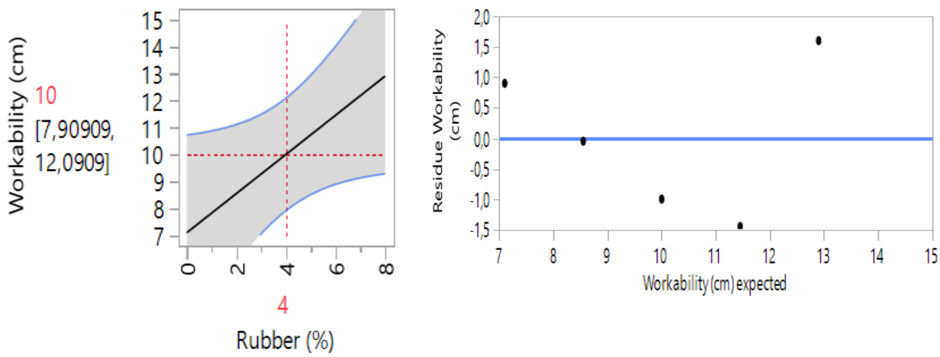
| | Workability | Fresh density | Air content | Compressive strength | Flexural strength | Ultrasonic velocity |
|---|---|---|---|---|---|---|
| $R^2$ | 0.76 | 0.98 | 0.95 | 0.92 | 0.93 | 0.97 |
| Adjusted $R^2$ | 0.68 | 0.97 | 0.94 | 0.89 | 0.91 | 0.96 |
| R MSE | 1.46 | 0.01 | 0.06 | 2.95 | 0.26 | 18.79 |
| Mean of Response | 10 | 2.29 | 1.52 | 34.09 | 5.86 | 3962.06 |

### 5.4 Workability

Figure 11a shows the main effects plots for the workability response of the concrete, taking into account the factors of the content of the rubber (%). It can be seen that the workability increases from 7.1 to 12.9 cm due to the change in the percentage of rubber from 0 to 8%. It was also seen that the rubber powder content has a positive effect on this response. These results agree with the mathematical equation, eq. 2.

$$Workability\ (cm) = 10 + 2.9\left(\frac{Rubber-4}{4}\right) \quad (2)$$

From the residue diagram as a function of the predicted values (graph 11b), it can be seen that normalized residuals are greater than +1.5 and less than -1.5. This suggests that there is a little discrepancy between the expected and experimental results in the chart.

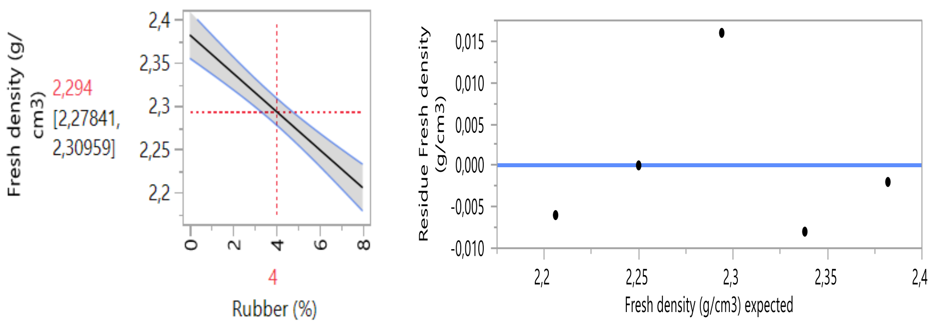



(a) (b)

Fig. 11. (a)Main effects plot, (b) graph perform the residues as a function of the predicted values

### 5.5 Fresh Density

Figure 12a shows the main effects plots for the fresh density response of the concrete. It can be noted that with an increase in the percentage of rubber from 0 to 8%, the fresh density decreases from 2.38 to 2.20 g/cm$^3$.




(a) (b)

Fig. 12. (a) Main effects plot (b) graph perform the residues as a function of the predicted values

It has also been observed that the content of rubber powder has an influence on the response, which shows that when increasing the amount of rubber, the density decreases. These results agree with the mathematical equation Eq. 3;

$$Fresh\ density\ (g/cm3) = 2.294 - 0.088\left(\frac{Rubber-4}{4}\right) \tag{3}$$

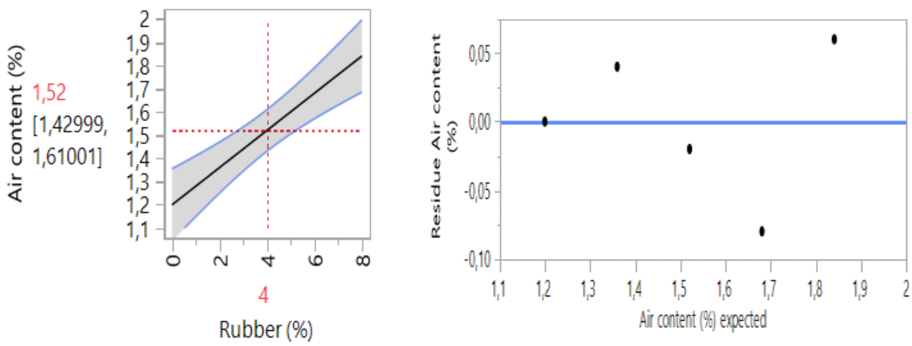
From the graph 12b of the residues as a function of the predicted values, it is quite clear that normalized residuals are greater than +0.015 and less than -0.010. The model indicates a negligible difference between the experimental value and the adjusted value.

### 5.6 Air Content

From figure 13a, it can be noted that the air content increases from 1.2 to 1.8% with an increase in the percentage of rubber from 0 to 8%. While the increase in the content of rubber powder has a slight influence on the air content. These results agree with the mathematical equation Eq. 4;

$$Air\ content\ (\%) = 1.52 + 0.32\left(\frac{Rubber-4}{4}\right) \tag{4}$$

It is pretty obvious from the graph 13b showing the residues as a function of the expected values that the normalized residuals are greater than +0.05 and smaller than -0.1. It indicates that the points are distributed consistently along the diagonal. This indicates the convergence of the experimental and numerical results.



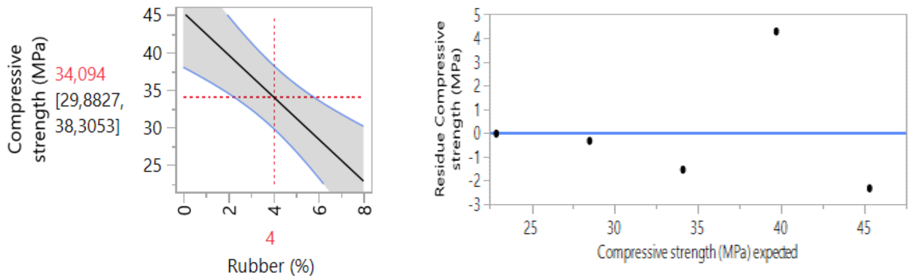

(a) (b)

Fig. 13. (a) Main effects plot (b) graph perform the residues as a function of the predicted values

### 5.7 Compressive Strength

Figure 14a shows the main effect plots for the compressive strength response of the concrete. Show clearly that the increase in rubber powder decreases the compressive strength; remarkably, indeed, the content of rubber powder presents a high negative effect on the response. As can be seen, there was a significant decrease in the compressive strength from 45.30 to 22.88 MPa due to the change in the percentage of rubber from 0 to 8%. These results agree with the mathematical equation Eq. 5;

$$Compressive\ strength\ (MPa) = 34.094 - 11.208\left(\frac{Rubber-4}{4}\right) \tag{5}$$




(a) (b)

Fig. 14. (a) Main effects plot (b) graph perform the residues as a function of the predicted values

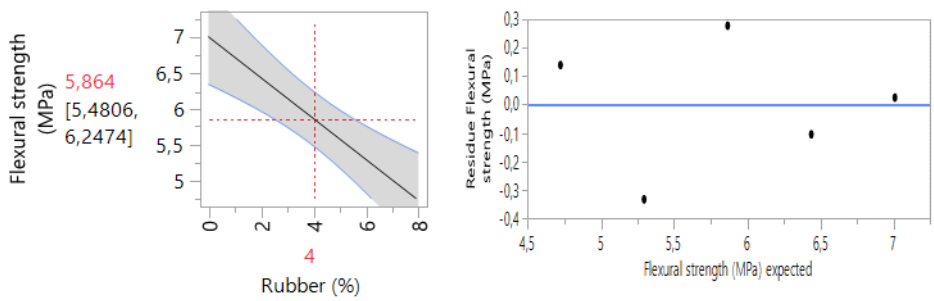
From the graph 14b, which shows the residues as a function of the predicted values, it is quite clear that normalized residuals are greater than +4 and less than -3. There are no points dispersed, and the points are distributed consistently along the diagonal.

### 5.8 Flexural Strength

Figure 15a shows the main effect plots for the flexural strength response. It can be noted that the flexural strength decreases from 7 to 4.72 MPa with increasing the percentage of rubber from 0 to 8%. It may be noted that the rubber powder has a small negative effect on this response. These results agree with the mathematical equation Eq. 6;

$$Flexural\ strength\ (MPa) = 5.864 - 1.142\left(\frac{Rubber - 4}{4}\right) \quad (6)$$

From the residue diagram as a function of the predicted values (graph 15b), it was seen that normalized residues were greater than +0.3 and less than -0.4. The model indicates a negligible difference between the experimental value and the adjusted value.




(a) (b)

Fig. 15. (a) Main effects plot (b) graph perform the residues as a function of the predicted values

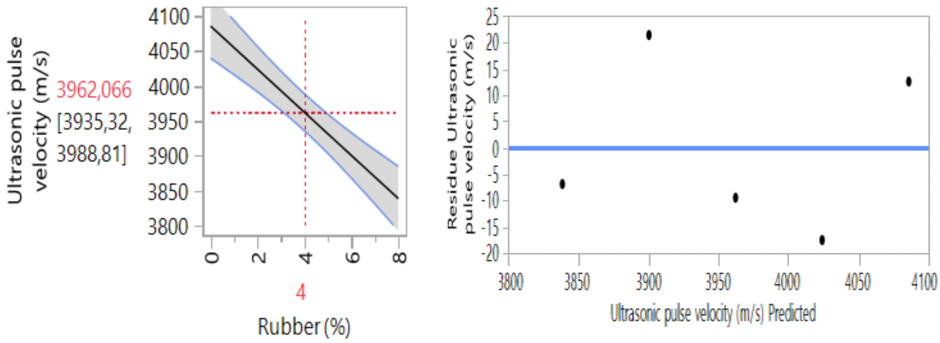
### 5.9 Ultrasonic Pulse Velocity

Figure 16a shows the main effect plots for the ultrasonic pulse velocity response of the concrete, taking into account the factors of the content of the rubber (%). It can be seen

that the ultrasonic pulse velocity decreases from 4085.81 to 3838.32 m/s with increasing the percentage of rubber from 0 to 8%.
The increase in the content of rubber powder has a small influence on the response. These results agree with the mathematical equation
Eq. 7;

$$Ultrasonic\ pulse\ velocity\ (m/s) = 3962.066 - 123.744\left(\frac{Rubber-4}{4}\right) \quad (7)$$

From the residue diagram as a function of the predicted values (graph 16b), it was seen that normalized residues were greater than +20 and less than -20. Thus, the planned model specifies an insignificant discrepancy between the adjusted value and the experimental value.




(a) (b)

Fig. 16. (a) Main effects plot (b) graph perform the residues as a function of the predicted values

### 5.10 Comparison of Predicted Values with Experimental Values Using the JMP Model

After presenting the results, it is noted that the deviation of the prediction values compared to the experimental values is acceptable.

Table 13. Workability

| N | Rubber (%) | workability (cm) | Predicted Workability (cm) | Residue Workability (cm) |
|---|---|---|---|---|
| 1 | 0 | 8 | 7.1 | 0.9 |
| 2 | 2 | 8.5 | 8.55 | -0.05 |
| 3 | 4 | 9 | 10 | -1 |
| 4 | 6 | 10 | 11.45 | -1.45 |
| 5 | 8 | 14.5 | 12.9 | 1.6 |

Table 14. Fresh density

| N | Rubber (%) | Predicted density(g/cm³) | Residue Density (g/cm³) | Residue Fresh density (g/cm³) |
|---|---|---|---|---|
| 1 | 0 | 2.38 | 2.382 | -0.002 |
| 2 | 2 | 2.33 | 2.338 | -0.008 |
| 3 | 4 | 2.31 | 2.294 | 0.016 |
| 4 | 6 | 2.25 | 2.25 | 0 |
| 5 | 8 | 2.20 | 2.206 | -0.006 |

Table 15. Air content

| N | Rubber (%) | Air content (%) | Predicted Air content (%) | Residue Air content (%) |
|---|---|---|---|---|
| 1 | 0 | 1.2 | 1.20 | 0 |
| 2 | 2 | 1.4 | 1.36 | 0.04 |
| 3 | 4 | 1.5 | 1.52 | -0.02 |
| 4 | 6 | 1.6 | 1.68 | 1.68 |
| 5 | 8 | 1.9 | 1.84 | 0.06 |

Table 16. Compressive strength

| N | Rubber (%) | Compressive Strength (MPa) | Predicted compressive strength (MPa) | Residue Compressive Strength (MPa) |
|---|---|---|---|---|
| 1 | 0 | 42.96 | 45.302 | -2.342 |
| 2 | 2 | 43.97 | 39.698 | 4.272 |
| 3 | 4 | 32.54 | 34.094 | -1.554 |
| 4 | 6 | 28.15 | 28.48 | -0.34 |
| 5 | 8 | 22.85 | 22.886 | -0.036 |

Table 17. Flexural strength

| N | Rubber (%) | Flexural Strength (MPa) | Predicted Flexural Strength (MPa) | Residue Flexural Strength (MPa) |
|---|---|---|---|---|
| 1 | 0 | 7.03 | 7.006 | 0.024 |
| 2 | 2 | 6.33 | 6.435 | -0.105 |
| 3 | 4 | 6.14 | 5.864 | 0.276 |
| 4 | 6 | 4.96 | 5.293 | -0.333 |
| 5 | 8 | 4.86 | 4.722 | 0.138 |

Table 18. Ultrasonic pulse velocity

| N | Rubber (%) | Ultrasonic (m/s) | Predicted Ultrasonic (m/s) | Residue Ultrasonic (m/s) |
|---|---|---|---|---|
| 1 | 0 | 4098.36 | 4085.810 | 12.55 |
| 2 | 2 | 4006.41 | 4023.938 | -17.528 |
| 3 | 4 | 3952.57 | 3962.066 | -9.496 |
| 4 | 6 | 3921.57 | 3900.066 | 21.376 |
| 5 | 8 | 3831.42 | 3838.322 | -6.902 |

## 6. Conclusion

Based on the experimental results obtained and numerical modeling in the current study of concrete containing waste rubber in the proportions of 0%, 2%, 4%, 6%, and 8%, the following conclusions were drawn:

The workability and air content of concrete increase with the increase in the levels of rubber powder. Partial cement replacement with rubber powder by 2%, 4%, 6%, and 8% led to a decrease in the fresh density of 2.10%, 2.94%, 5.46%, and 7.56%, respectively, compared to the reference concrete. Using rubber powder in concrete decreases the compressive strength with an increase in the amount of rubber, the decrease in compressive strength is 47% for concrete containing 8% of rubber when compared to the reference concrete.

The flexural strength decreases by 10%, 13%, 29.44%, and 30.86% for replacement levels of rubber powder of 2%, 4%, 6%, and 8%, respectively, compared to the reference concrete. As the replacement ratio of rubber powder in concrete increases, the ultrasonic pulse velocity decreases by 2.24%, 3.55%, 4.31%, and 6.51% for replacement levels of rubber powder of 2%, 4%, 6%, and 8%, respectively, compared to the reference concrete.

Adding 2% rubber waste to the concrete gave it good strength, greater than normal concrete strength. Statistical parameters show good correlation coefficients ($R^2$= 0.76; 0.98; 0.95; 0.92; 0.93; and 0.97) for workability, fresh density, air content, compressive strength, flexural strength, and ultrasonic pulse velocity, respectively. The values of ($R^2$) are close to 1, which shows a good correlation between the predicted and experimental models. This leads us to the conclusion that the model in use is reliable and effective at predicting the effect of waste rubber on concrete that has been examined for its mechanical and physical properties.

This study provides valuable information about the use of this numerical model in the field of civil engineering in order to obtain reliable and accurate results.

## Acknowledgements

The authors are extremely appreciative of the University of SKIKDA and the University of Bordj Bou Arreridj, Algeria.

## References

[1] Siddika A,Al Mamun Md, Alyousef R ,Mugahed Amran Y,Aslani F, Alabduljabbar H. Properties and utilizations of waste tire rubber in concrete: A review.Construction and Building Materials, 2019; 224: 711- 731. https://doi.org/10.1016/j.conbuildmat.2019.07.108

[2] Raffoul S, Garcia R, Escolano-Margarit D, Guadagnini M, Hajirasouliha I, Pilakoutas K. Behaviour of unconfined and FRP-confined rubberised concrete in axial compression. Construction and Building Materials, 2017; 147: 388- 397. https://doi.org/10.1016/j.conbuildmat.2017.04.175

[3] Ferronato N, Torretta V. Waste Mismanagement in Developing Countries: A Review of Global Issues. International Journal of Environmental Research and Public Health, 2019; 16(6), 1060. https://doi.org/10.3390/ijerph16061060

[4] Mohajerani A, Burnett L, Smith J. V, Markovski S, Rodwell G, Rahman M. T, Kurmus H, Mirzababaei M, Arulrajah A, Horpibulsuk S, Maghool F. Recycling waste rubber tyres in construction materials and associated environmental considerations: A review. Resources, Conservation and Recycling, 2020; 155, 104679. https://doi.org/10.1016/j.resconrec.2020.104679

[5] Bisht K, Ramana P.V. Evaluation of mechanical and durability properties of crumb rubber concrete.Construction and Building Materials. 2017:155:811-817. https://doi.org/10.1016/j.conbuildmat.2017.08.131
[6] Guelmine L, Hadjab H, Benazzouk A. Effect of elevated temperatures on physical and mechanical properties of recycled rubber mortar. Construction and Building Materials. 2016; 126: 77-85. https://doi.org/10.1016/j.conbuildmat.2016.09.018
[7] Dong Q,Huang B, Shu X. Rubber modified concrete improved by chemically active coating and silane coupling agent. Construction and Building Materials.2013:48:116-123. https://doi.org/10.1016/j.conbuildmat.2013.06.072
[8] Al-Tayeb M. M, Abu Bakar B. H, Akil H. M, Ismail H. Effect of Partial Replacements of Sand and Cement by Waste Rubber on the Fracture Characteristics of Concrete. Polymer-Plastics Technology and Engineering, 2012. 51(6), 583-589. https://doi.org/10.1080/03602559.2012.659307
[9] Wang HY. Chen BT. Wu YW. A study of the fresh properties of controlled lowstrength rubber lightweight aggregate concrete (CLSRLC). Constr Build Mater 2013;41:526-31. https://doi.org/10.1016/j.conbuildmat.2012.11.113
[10] Steyn Z.C, Babafemi A.J,Fataar H, Combrinck R. Concrete containing waste recycled glass, plastic and rubber as sand replacement. Construction and Building Materials, 2020, Volume, 269, 121242. https://doi.org/10.1016/j.conbuildmat.2020.121242
[11] Pelisser F, Zavarise N,Longo TA,Bernarin AM. Concrete made with recycled tire rubber: effect of alkaline activation and silica fume addition. Journal of Cleaner Production, 2011; 19: 757-763. https://doi.org/10.1016/j.jclepro.2010.11.014
[12] Gupta T, Siddique S,Sharma R, Chaudhary S. Investigating mechanical properties and durability of concrete containing recycled rubber ash and fibers. Journal of Material Cycles and Waste Management, 2021; 23: 1048-1057. https://doi.org/10.1007/s10163-021-01192-w
[13] Singh G, Tiwary A. K, Singh S, Kumar R, Chohan J. S, Sharma S, Li C, Sharma P, Deifalla A. F. Incorporation of Silica Fumes and Waste Glass Powder on Concrete Properties Containing Crumb Rubber as a Partial Replacement of Fine Aggregates. Sustainability, 2022; 14(21), 14453. https://doi.org/10.3390/su142114453
[14] Bisht K, Ramana P. Waste to resource conversion of crumb rubber for production of sulphuric acid resistant concrete. Construction and Building Materials, 2019; 194, 276-286. https://doi.org/10.1016/j.conbuildmat.2018.11.040
[15] Pavankalyan K, Durga Prasad R, Pradeep Kumar S. Mechanical and Durability Studies on Concretes Containing Crumb Rubber Fine Aggregate. IOP Conference Series: Earth and Environmental Science, 2022; 1086(1), 012013. https://doi.org/10.1088/1755-1315/1086/1/012013
[16] Najim KH,Hall M. Mechanical and dynamic properties of self-compacting crumb rubber modified concrete. Construction and Building Materials, 2012; 27:521-530. https://doi.org/10.1016/j.conbuildmat.2011.07.013
[17] Azimi-Pour M, Eskandari-Naddaf H. Synergistic effect of colloidal nano and micro-silica on the microstructure and mechanical properties of mortar using full factorial design. Constr. Build. Mater, 2020; 261,120497. https://doi.org/10.1016/j.conbuildmat.2020.120497
[18] Mutuk T, Mesci B. Analysis of mechanical properties of cement containing boron waste and rice husk ash using full factorial design. J. Clean. Prod. 2014; 69, 128-132. https://doi.org/10.1016/j.jclepro.2014.01.051
[19] Liu M. L, Zhang G. D, Ding Y. F, Wei L, Wang Y, Zhang X. Z. Research on Properties of the Concrete with Waste Rubber Powder. Materials Science Forum, 2016; 852, 1443-1449. https://doi.org/10.4028/www.scientific.net/MSF.852.1443

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

[21] Dong Q, Huang B, Shu X. Rubber modified concrete improved by chemically active coating and silane coupling agent. Construction and Building Materials, 2013; 48:116-123. https://doi.org/10.1016/j.conbuildmat.2013.06.072

[22] Chylík R, Trtík T, Fládr J, Bílý P. Mechanical properties and durability of crumb rubber concrete, IOP Conf. Series: Materials Science and Engineering, 2017; 236:012093. https://doi.org/10.1088/1757-899X/236/1/012093

[23] Abdullah S. R.EFFECT OF RUBBER POWDER PARTICLE ON THE STRENGTH OF FOAMED CONCRETE. International Journal of GEOMATE, 2017; 13(38). https://doi.org/10.21660/2017.38.80292

[24] Li W, Wang X. C, Zhang J. P. An Overview of the Study and Application of Rubberized Portland Cement Concrete. Advanced Materials Research, 2012; 598, 374-378. https://doi.org/10.4028/www.scientific.net/AMR.598.374

[25] Sof A. Effect of waste tyre rubber on mechanical and durability properties of concrete - A review. Ain Shams Engineering Journal, 2018; 9:2691-2700. https://doi.org/10.1016/j.asej.2017.08.007

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

[27] Si R,Wang J,Guo Sh,Dai Q,Han S. Evaluation of Laboratory Performance of Self-Consolidating Concrete with Recycled Tire Rubber. Journal of Cleaner Production,2018.P.823-831. https://doi.org/10.1016/j.jclepro.2018.01.180

[28] Najim K.B, Hall M.R. Mechanical and dynamic properties of self-compacting crumb rubber modified concrete. Constr. Build. Mater, 2012; 27:521-530. https://doi.org/10.1016/j.conbuildmat.2011.07.013

[29] Nordstokke D, Colp S.M. Factorial Design Encyclopedia of Quality of Life and Well-Being Research, 2014; 2144-2145. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-0753-5_982

[30] Gelis K, Ozbek K, Celik, A.N, Ozyurt O. A novel cooler block design for photovoltaic thermal systems and performance evaluation using factorial design. J. Build. Eng, 2021; 48, 10. https://doi.org/10.1016/j.jobe.2021.103928