



Research Article

Prediction performance of multiple linear regression analysis applied to the mechanical properties of green cement mortar

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ABSTRACT

The application of the mathematical tools such as multiple linear regression analysis (MLR) in the prediction of mechanical behavior of cement-based materials is the subject of several previous investigations works conducted in civil engineering field. As new alternative of the development of green cement mortar, this work aims in the first to study the effect of the substitution of Ordinary Portland Cement (OPC) with ground granulated blast furnace slag (GGBFS) on the compressive and flexural strength of manufactured mortar. Both mechanical tests are carried out using cubic and prismatic specimens with dimensions of $4\text{ cm} \times 4\text{ cm} \times 4\text{ cm}$ and $4\text{ cm} \times 4\text{ cm} \times 16\text{ cm}$, respectively. In the other hand, this study investigates the capacity of the multiple linear regression analysis in the prediction of compressive and flexural strength of green cement mortars. Indeed, tests samples of 64 are examined in order to develop an adequate mathematical model for the prediction of the both investigated mechanical properties as a function of the three independents variables of water/binder ratio, hydration ages and the concentration of ground granulated blast furnace slag. The mechanical tests revealed that 20 mass % of ground granulated blast furnace slag content give good properties for the development cement mortars and above this concentration there is a slight effect on the mechanical strength. According to the statistical results, this study concluded also that the multiple linear regression analysis has a good performance for the prediction of flexural strength properties than compressive strength of green cement mortars, 0.8 and 0.42 of coefficient of determination (R^2) are obtained, respectively. In addition, the experimental results revealed also that the hydration age has more effect than the two others parameters which is in accordance with statistical results obtained from the MLR analysis, such as significance level (Sig.), standardized coefficients, t-test values and the variation inflation factor (VIF). Both regression models obtained for compressive and flexural strength are statically significant with very low values of sig. $< 5\%$. The statistical parameters indicate clearly that the hydration age has a strong effect on the prediction of compressive and flexural strength values using the obtained models, which mainly due to its highest values of standardized coefficients of 0.61. The results of these parameters indicate that water/binder ratios have more effect than ground granulated blast furnace slag content with standardized coefficients values of 0.13 and -0.17, respectively, but this is not the same for the flexural strength values, the concentration of ground granulated blast furnace slag has more effect than water/binder ratios, -0.22 and -0.66, respectively.

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INTRODUCTION

In the recent decade, there are considerable attention has been focused on the addition of the GGBFS in the composition of cementitious materials as a supplementary additive due to its several advantages like: enhanced the durability, workability, ecological and environmental benefits of cementitious materials [1–4]. Its chemical and physical properties mainly depend on the raw materials and the freezing process is chosen to cool down the molten materials [5, 6]. According to the EN 15167-1 (2006) standard [6], this raw material is obtained by quick freezing of a slag melt of appropriate composition, synthesized by smelting iron ore in a blast furnace with high hydraulic properties. Moreover, GGBFS mainly contain different oxides like calcium oxide (CaO), silicon dioxide (SiO₂) and magnesium oxide (MgO) with mass ratio of (CaO + MgO)/(SiO₂) equal to 1. As well the aluminum oxide (Al₂O₃) and small concentration of other compounds can be present in this material. In contrast, GGBFS conforming to this European Standard must contain no added materials except grinding aids to assist in the manufacture. Indeed, the concentration of grinding aid and the organic of any grinding aid(s) shall not higher than 1.0 and 0.2% by weight of GGBS, respectively.

Based on the previous studies, numerous scientific research styles were conducted to understand the effect of GGBFS content on the mechanical characteristics of cement mortar (Table 1), it was clearly revealed from the most results of these experimental studies that GGBFS addition have a

positive effect on the mechanical properties of mortars due mainly to its good quality of granulometry and chemical hydration (Table 2) [7–16]. Barnett et al. [15] studied the effect of different parameters like: GGBFS content, curing temperature and water to binder ratio on the mechanical strength development of mortars containing GGBFS and OPC. The authors concluded in this work that GGBFS content and water-binder ratios affected the estimated strength with a similar degree. In contrast, the results indicated that just the parameter of curing temperature that significantly affect the mechanical properties of manufactured mortars mixing of GGBFS and OPC. Different investigation works concluded that the GGBFS mortars gain strength faster at high temperature while under standard curing conditions. Çakır et al. [12] studied the effect of curing conditions on properties of mortars without and with different amount of GGBFS, namely 0% (control), 30%, and 60% by weight. In this work, the mechanical properties like flexural and compressive strength are investigated for the samples with the age of 7, 28, 56, 90, and 180 days. The results of this work concluded that the addition of GGBFS has a significant effect on the final properties of studied mortars. The results indicate that the effect of high temperature and lower relative humidity conditions on the flexural and compressive strength properties are more important specially in slag as a partial replacement of cement mortars. Akçaözoglu et al. [17] investigated the combination effect of GBFS and fly ash addition on the mechanical properties of studied

Table 1. Summary of mechanical properties of mortar containing different amount of GGBFS

Ref.	GGBFS content (%)	w/b Ratio	Hydration age (days)	Compressive strength (MPa)	Flexural strength (MPa)
[26]	0, 30, 50, 70	0.5	30, 60, 90, 120 and 150	34 to 51	/
[10]	0, 5, 10, 15, 20	0.5	3, 7, 14 and 28	26, 32, 29, 22, 19	/
[9]	0, 60, 70, 80	0.5	7, 14, 28, 90	40 to 71	/
[27]	10, 30, 50	0.3	2, 14, 28	6 to 70	2 to 9
[28]	10, 20, 30, 40, 50, 60 and 70	0.45 and 0.65	28	26 to 47	/
[29]	2, 4, 6, 8 and 10	0.27	28	40 to 43	/
[2]	0, 20, 40, 60 and 80	0.3, 0.4 and 0.5	3, 7, 28, 90 and 360	12.1 to 90	/
[30]	0, 10, 20, 30 and 40	0.5	2, 7, 28, 90 and 180	7 to 68	1.8 to 9.2
[1]	25 to 60	0.31 and 0.38	3, 7 and 28	5 to 84	/
[31]	55, 60 and 65	0.3, 0.4 and 0.5	7 and 28	16 to 51	3 to 7.3

Table 2. Physical characteristics and chemical composition and of cement starting powder

Physical properties	Color	Bulk density (kg/m³)		specific gravity		Blaine's fineness (cm²/g)			
Cement	Off-white	1440		3.1		3500			
Chemical composition									
Oxides	CaO	SiO₂	Al₂O₃	MgO	Fe₂O₃	MnO	TiO₂	SO₃	Loss on Ignition
Content (%mass)	61.40	22.07	5.7	2.17	2.62	/	/	/	6.0

mortars containing the aggregate of waste Poly-ethylene Terephthalate (PET) bottle. Based to the most results obtained in this work, the incorporation of GGBFS raw materials have a good effect on the mechanical characteristics of studied mortars cured during more than 90 days. Işıkdağ et al. [13] studied the addition effect of GGBS on the different properties of Horasan mortars. The results of this investigation indicates clearly that a significant improvement of mechanical and physical properties was obtained for the specimens with GGBFS addition compared to the other control samples. Recently, Nojoukambari et al. [18] studied the partial replacement of cement with Feldspar and GGBFS in order to improve different characteristics of mortar such as the mechanical and the durability properties. Different amount of Feldspar and GGBS content are used in this work for manufacturing 20 mixtures with 10%, 20%, and 30% by weight of cement. The must conclusions obtained in this work indicate clearly that the mortar samples with 10% of Feldspar and 30% of GGBFS contents exhibit more good properties than the others ternary mixtures.

In the recent decades, different investigation research conducted about the properties prediction of cementitious materials [19–23]. For that purpose, there are several analysis methods for modelling these properties, including computational modelling, statistical methods, and different recent developed tools such as regression analysis and machine learning techniques. Among the most traditional methods widely used for the prediction of the mechanical properties of cementitious materials, the MLR received a lot of attention in this field [22, 24]. The most important characteristic of this analysis is the ability to evaluates the relationship between the dependent (Y) and two or more independent variables (X). Recently, Palod et al. [25] developed a mathematical model by applying a MLR analysis in order to study the influence replacing cement with different proportions of GGBFS on the compressive strength of cementitious materials cured during 28 days. The obtained model presents high values of coefficient of determination (R^2) of 0.916, which explain the high precision of the developed equation for the prediction of the studied mechanical characteristic. Therefore, the authors conclude in this work that the obtained MLR model can be used for the estimation of the compressive strength property of any ternary mortar cured at the 28 days and manufactured by partially replacement of cement with GGBFS and steel slag.

The main objective of this work is to study the capacity of MLR analysis on the prediction of the mechanical properties of mortars with different GGBFS additions used as sustainable cementitious binder for the production of eco-friendly mortar. For this purpose, three concentrations of GGBFS were added of 10%, 20%, and 30% by weight of cement. The mechanical tests of compressive and flexural strength are carried out on the specimens with different hydration ages of 3, 7, 28 and 90 days. In addition, four w/b ratios of 0.35, 0.40, 0.45 and 0.50 were considered to evaluate the more efficient ratio (Table 1) [26, 31].

MATERIALS AND METHODS

Materials

Cement

The selected cement in the present work was the OPC 52.5 N conforming to CEM Type 1. The physical characteristics and the chemical composition of this raw material are indicated in Table 2. Moreover, the particle size distribution of used cement was obtained using Mastersizer 2000 laser diffraction particle size analyzer (Malvern Instruments Ltd., Malvern, UK).

GGBFS powder

The GGBFS used in the study was obtained from Ecocem company (from the plant of Fos sur mer, France). Table 3 summarizes the chemical composition and the physical characteristics of this element addition. It can be seen from these results that the GGBFS used in this study is in agreement with the requirements of EN 15167-1 [6]. Indeed, the results appear that the ratio of $(\text{CaO}+\text{MgO}) / \text{SiO}_2$ is higher than 1.0 and the presence of other oxides of MgO , SO_3 , Cl, sulfide, alkalis, LOI and H_2O are well respected. In the other hand, according to its physical properties, it is classified as a category 80 of slag [32]. A laser diffraction particle size analyzer (Mastersizer 2000, Malvern Instruments Ltd., Malvern, UK) was also used to identify the particle size distribution of GGBFS powder.

Aggregates

Two types of natural sand with a continuous intermediate grade were selected for this work as coarse (CA) and fine aggregate (FA), which are provided from SARL FIAS,

Table 3. Characteristics of GGBFS powder

Physical properties	Color	Bulk density (kg/m³)		specific gravity		Blaine's fineness (cm²/g)						
GGBFS	grey	1200		2.9		4500						
Chemical composition												
Oxides	CaO	SiO₂	Al₂O₃	MgO	Fe₂O₃	MnO	TiO₂	SO₃	Cl	S₂.	Na₂O éq.	Loss on Ignition
Content (%mass)	42.7	36.7	11.3	7.0	0.6	0.3	0.5	0.2	0.01	1.0	0.7	2.0

Keddara-Boumerdes, Algeria. As indicated in the Table 4, the CA present a specific gravity and fineness modulus of 2.43 and 2.8, respectively. In the other hand, FA shows a specific gravity and fineness modulus of 2.63 and 1.12. The water adsorption values of each aggregate were found to be 11.92 and 4.3 % for CA and FA, respectively.

Superplasticizer (SP)

A commercial superplasticizer (Sika ViscoCrete TEMPO-12) with acrylic copolymer is used in this study, with special characteristics summarized in Table 5.

Water

The water used for mixing and curing purposes presents a good quality potable water.

Mixture Proportions and Specimen Preparation

In order to examine the effect of GGBFS addition as partial substitution of cement on the mechanical properties of prepared mortars, different proportions are used to substitute cement in specimen mixtures which varied from 0 to 30% replacement by weight of cement (10%, 20%

and 30%). Four various ratios of water-to-binder (cement + GGBFS) mass of mortar were applied, specifically 0.35, 0.40, 0.45 and 0.50 (Table 6 and Fig. 1). A superplasticizer based acrylic copolymer was added with different content as indicated in Table 6 to obtain the systematic workability; the admixture dosage in each mix was varied to achieve the target flow of 20 cm. The required superplasticizer content was determined by using mini-cone test. More details about the designation of specimens and mixtures proportions details are given in Table 6. After mixing, prismatic and cubic specimens with 4 x 4 x 16 cm dimensions were prepared from both OPC and GGBFS/OPC mortars for all the testing measurements, this preparation method is made with according to EN 196-1 [33].

All mixtures were prepared according to the following steps: i) various amount of GGBS and cement were initially dissolved in water and mixed for 4 min with respecting different studied w/b ratios. In this work, the OPC was substituted by GGBFS by weight percentage of 10 wt%, 20 wt% and 30 wt%; ii) then the sand content is added each mortar mixes; iii) and finally superplasticizer was added in order

Table 4. Physical characteristics of aggregates

Sand	specific gravity	Bulk density [kg/m ³]	Water absorption [%]	Sand Equivalent [%]	Fineness Modulus
(CA)	2.43	1.64	11.92	67	2.8
(FA)	2.63	1560	4.30	86	1.12

Table 5. Characteristics of Sika ViscoCrete TEMPO-12 superplasticizer

Color	pH	Density	Cl-	Na ₂ O éq.	Standard/Agreement
Light to dark brown liquid	4.5 ± 1.0	1.06 ± 0.01	≤ 0.1 %	≤ 1 %	- EN 934-2 (2009) [33] - CNERIB : DTEM/108/2017

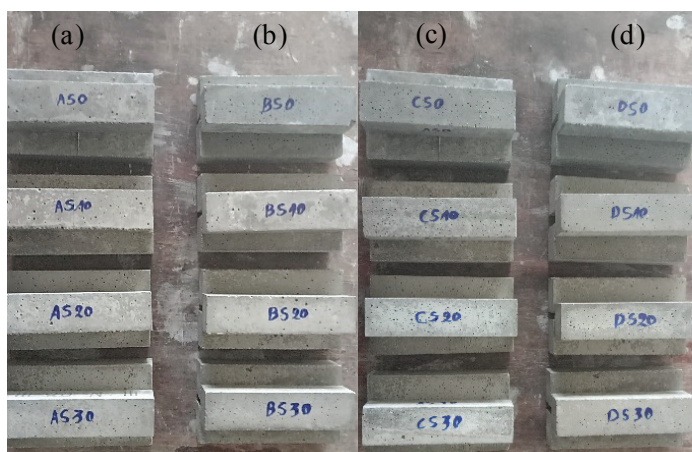


Figure 1. Mortar specimens with various water-to-binder ratio: (a) 0.35 (b) 0.40, (c) 0.45 and (d) 0.50.

Table 6. Mixture proportions of different mortars samples

Formulation	Composition [kg/m ³]				Parameters				
	Coarse Sand	Fine sand	Cement	GGBFS	Water	SP	C:S	w/b	SP [%]
AS0	1304	88	464	0	258	2.0	3:1	0.50	0.45
AS10			417	46					
AS20			372	92					
AS30			325	139					
BS0	1336	90	475	0	238	4.3	3:1	0.45	0.90
BS10			427	48					
BS20			380	95					
BS30			360	142					
CS0	1353	92	487	0	216	6.8	3:1	0.40	1.4
CS10			438	49					
CS20			390	97					
CS30			341	146					
DS0	1404	94	499	0	194	8.6	3:1	0.35	1.7
DS10			449	50					
DS20			399	100					
DS30			349	150					

to obtain a good workability of manufactured mixture. The Sika ViscoCrete TEMPO-12 superplasticizer content was varied at the saturation dosage from 0.45 to 2 % by binder weight and mixed for 2 min. Table 6 summarized all the notations used in this paper for the mortar mix with and without GGBS for different curing times is mentioned in the nomenclature. The samples were cast and kept in steel molds during 24 h, and then they were demolded and cured at 23 °C in water as four sets for 3, 7, 28 and 90 days. Before testing, specimens were cured in water at 23 °C and 60% of relative humidity in a room with a constant temperature and humidity. The letter A, B, C and D indicated in the samples notation (see Table 6) correspond to 0.35, 0.40, 0.45 and 0.50, respectively. Then the letter S designate the GGBFS with its amount addition.

Mechanical Tests

In this study, two mechanical tests were carried out on the obtained GGBFS/cement mortars, namely compressive and flexural strength tests. Cubic and prismatic specimens with dimensions of 4 cm × 4 cm × 4 cm and 4 cm × 4 cm × 16 cm were manufactured for both analyses, respectively. These tests were performed for each mixing proportion with hydration ages of 3, 7, 28 and 90 curing days. All measurements for these mechanical tests were obtained using MTS criterion model 45 apparatus with crosshead loading capacity of 300 and 50 kN for compressive and flexural strength tests, respectively (Fig. 2).

Compressive strength test

Compressive strength tests are generally the most analysis that realized for studding the various properties of

cementitious materials, this is because the majority of its characteristics and the structural design are mainly related to this test. Indeed, the compressive strength analysis was performed according to BS EN 12390-3 [33], with controlled displacement at constant rate of 0.6 MPa/s. its values are obtained with the formula indicated in the equation (1).

$$f_c = \frac{F}{A_c} \quad (1)$$

where f_c presents the compressive strength [MPa]; F is the extreme load at the fracture point [N]; A_c is the cross-sectional surface area [mm²].

Flexural strength test

Generally, this test explains the stress occurred in a material just before it fails in flexure analysis, The measurement of flexural strength needs the insertion of the sample among two points or supports and starting a load using 3-Point Bend or 4-Point Bend testing. During this work, this test was carried out to evaluate the mechanical performance of the GGBFS-cement mortars according to BS EN 12390-5 [34]. The loading in three points was performed at a speed of 0.06 MPa/s, until failure. The flexural strength values were obtained using the following equation:

$$f_{ct, fl} = 1.5 * \frac{Fl}{bd^2} \quad (2)$$

where $f_{ct, fl}$ is the flexural strength with unit of [MPa]; F is the extreme load at the break level [N]; l is the length of the support [mm]; b is the width of the beam [mm]; d is the thickness of the beam [mm].

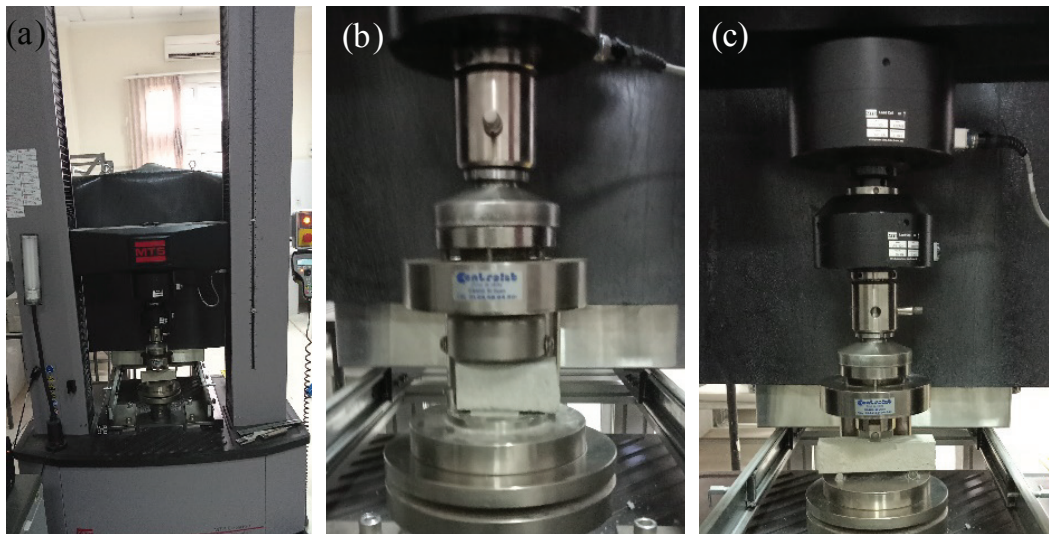


Figure 2. Mechanical tests equipment: (a) MTS criterion model 45 machine, electrohydraulic servo testing machine, (b) flexural test and (c) compressive test dispositive.

MLR Analysis

There is several engineering problems need the examination of the correlation between different studied variables. For this purpose, the MLR analysis is one of the most statistical tools which mainly adopted by several investigation research conducted in construction field for studying this correlation. In this case, the MLR method evaluates the relationship between the dependent (Y) and different independent variables (X) by an appropriate equation. For any application of MLR in the prediction models, the analysis aims to estimate and to express the variation of the dependent variable values as a function of the independent variables. The general form of MLR model can be expressed via the equation 3.

$$Y_i = b_0 + b_1X_1 + b_2X_2 + \dots + b_iX_i + \varepsilon_i = \sum_{i=1}^p b_iX_i + \varepsilon_i \quad (3)$$

where Y_i presents the dependent variable (compressive and flexural strength values), X_i , ($i=1,2,\dots,p$) indicates the independent variables (w/b ratio, hydration ages and GGBFS content); b_i , ($i=1,2,\dots,p$) are the parameters of the model and ε_i is the model random error. According to the literature, there are many software that can be used for the conception of the mathematical models by the application of MLR analysis, namely i) Excel of Microsoft; (ii) SPSS (Statistical Package for Social Sciences); (iii) Matlab of the MathWorks and (iv) NeuroSolutions of NeuroDimension [31]. The difference and the choice between of all these statistical tools are generally based on the two major parameters of the availability and the cost of software's acquisition. In this work, Excel and SPSS are used for application of MLR analysis due to its low cost and usually applied for construction calculation sector by the managers, planners, architects, etc. However, there are several methods that can

be able to define the relationship between the dependent and the independent variables using the MLR analysis, such as: Enter, stepwise, backward, forward, ..., etc. The enter method is chosen in this work for the investigation of regression model. Compared to the others methods, the enter regression technique considered all studied independent variables in the development of the mathematical model, which is defined sometimes as a simultaneous solution. In contrast, the stepwise method is statistical approaches programmed to add and remove different factors in the obtained models.

RESULTS AND DISCUSSION

Mechanical Strength Properties of Studied Mortar

Compressive strength evaluation

The obtained results of compressive strength of cement/GGBFS sand mortars with hydration ages of 3, 7, 28 and 90 days, and with different w/b ratios from 0.35 to 0.5 were presented in Figure 3. As expected, the compressive strength values of all mortar specimens increase with hydration age, from 34.91 to 88.33 MPa for the sample cured during 90 days, with 0.35 of w/b ration and 30 % of GGBFS. In addition, the results appear that these characteristics also mainly affected by w/b ratios and GGBFS contents. The increasing of w/b ratios from 0.35 to 0.5 has a negative effect on the compressive strength values of green manufactured mortars, which decrease from 50.8 to 30.29 MPa, respectively, for the specimen without GGBFS and 3 days of hydrations age. According to Singh et al. (2015), the mechanical properties of cement mortars decrease with increasing of w/b ratio [35]. At early age (3 and 7 of hydrations ages),

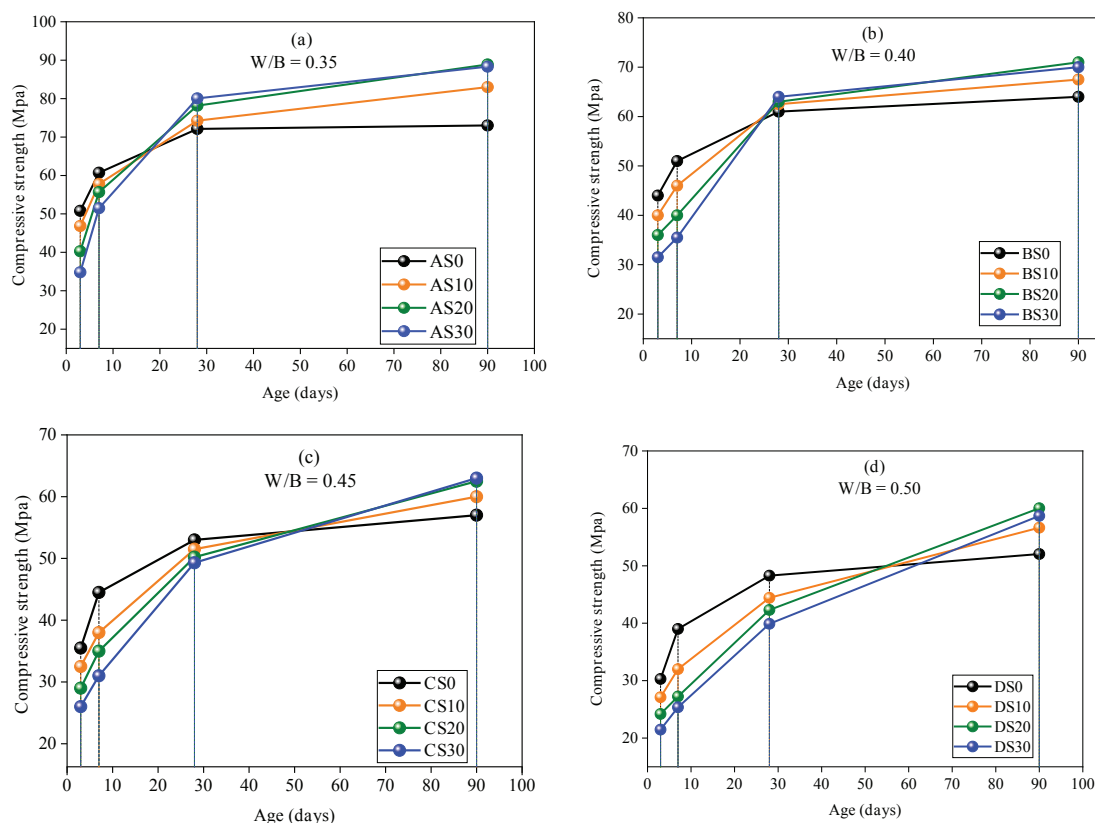


Figure 3. Compressive strength versus hydration age, GGBFS content and water-to-cement ratio from (a) to (d).

the substitution of cement by different amounts of GGBFS decrease considerably the compressive strength for all specimens cured at different of hydration ages and with w/b ratios. At 3 days of curing duration and 0.35 of w/b ratio, its values decrease from 50.8 to 34.81 MPa in the presence of 0 and 30 % of GGBFS, respectively. This result can be explained by the characteristics of GGBFS that have a low hydraulic reactivity at this interval of hydration age, which cement mortar could achieve a higher compressive strength value than the cement/GGBFS mixed mortars. The same conclusion is obtained by Yun et al. [14] during their work about the effect of hydration ages on the strength variation of GGBFS mortars. In contrast, at 28 and 90 days of hydrations ages, the compressive strength of all manufactured mortars with different w/b ratios improved with increasing of GGBS contents. At the hydration age of 90 days and 0.35 of w/b ratio, it increases from 73.01 to 88.89 MPa for the sample with 0 and 20 % of GGBS, respectively. This result is in accordance with the most investigated works conducted in this subject [1, 18]. This is mainly due to the chemical reaction of absorption phenomena occurred between OPC and GGBFS particles, this lead to the activation of hydraulic activity by reaction of GGBFS with moisture and free calcium hydroxide, $\text{Ca}(\text{OH})_2$ occurred from the hydration of cement to obtaine more binding phase of calcium silicate hydrate (CSH). In addition, the presence of

GGBFS particles in the mortars samples stimulate the pozzolanic reaction by the high concentration of SiO_2 present in GGBFS [36], the amount of Ca^{2+} ions obtained by the hydration reaction became improved at internal interfaces of mortars samples. The active SiO_2 of GGBFS combined with Ca^{2+} ions produce much higher amount of stable C-S-H, which increases the compressive strength values of studied samples. As a conclusion, the results illustrated in Figure 3 indicate clearly that at early age of hydration there is no effect between the variation of w/b ratios and GGBFS addition, the compressive strength decrease 40 % when w/b ratio increase from 0.35 to 0.5 for mortar with and without GGBFS contents. In contrast, at 90 days of hydration ages, the compressive strength decreases 28,7 % and 32,5 for mortars without and with 20 % of optimal amount of GGBFS.

Figure 4 demonstrates the frequency histograms of compressive strength results of GGBFS-cement mortars samples. According to 64 tests of compressive strength property deduced from studied mortars, the values of this characteristic varied from 0 to 90 MPa with median of 51.26 MPa and standard deviation of 18.06 MPa.

Figure 5 shows the results of the particle size distribution of both CEM 1 and GGBFS powders. An average particle size (d_{50}) of 6.223 and 10.154 μm were obtained for CEM 1 and the GGBFS, respectively, which indicates that GGBFS

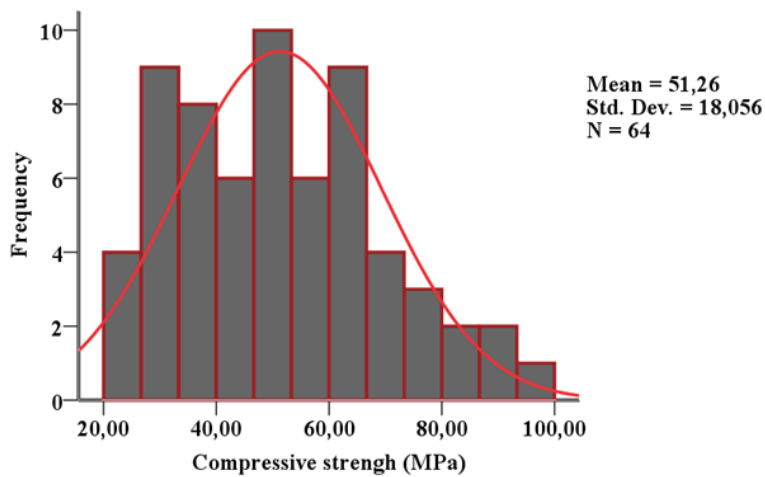


Figure 4. Frequency histogram of compressive strength values.

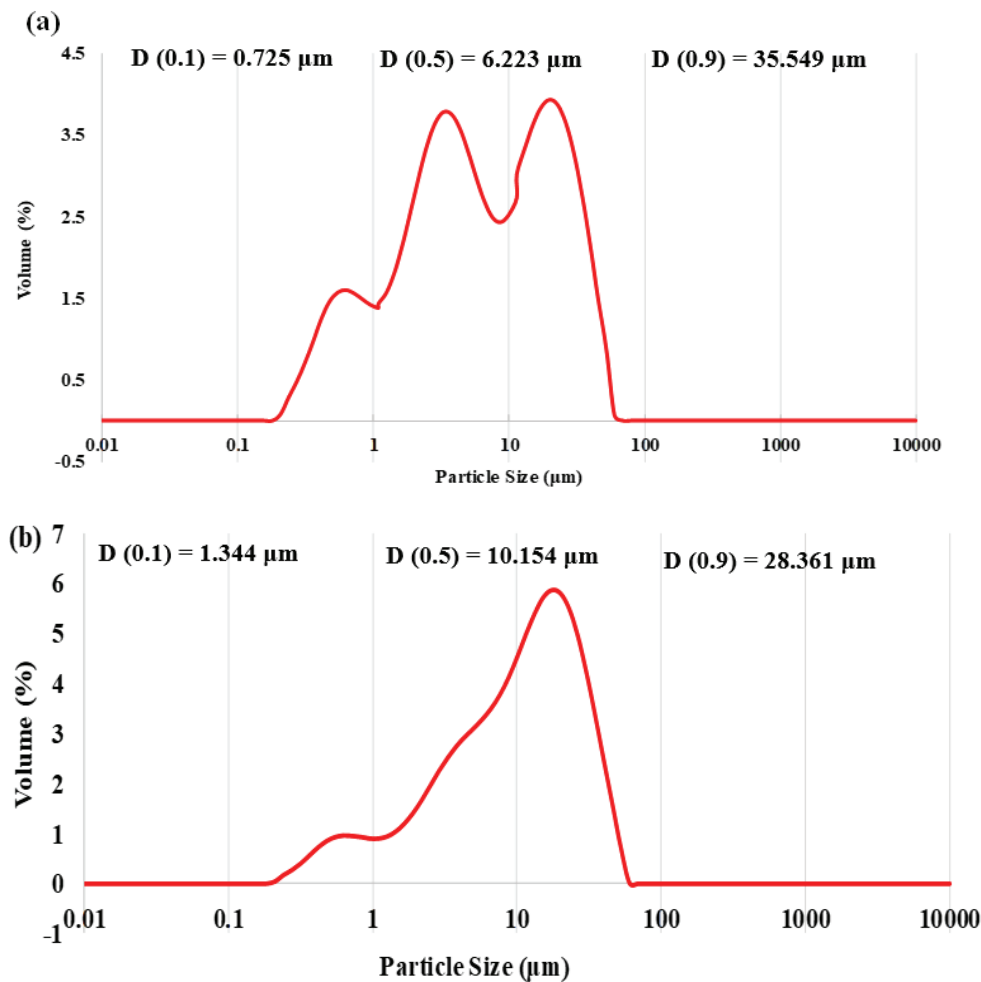


Figure 5. The particle size distribution of (a) CEM 1 and (b) GGBFS.

had a high particles size than CEM 1. These findings are in agreement with the interpretation result of compressive strength characteristic of manufactured mortars. However,

many previous experimental researches have indicated that the particle size of GGBFS has significant effect on the compressive strength of mortar [37, 38]. The study conducted

by Zhu et al. [36] concluded that with increasing the particle size of GGBFS the compressive strength values increase significantly, due to the high exposure of its surface area to the pozzolanic reactions. Moreover, the optimal amount of cement replacement that can be obtained after 28 and 90 days of hydration ages was only 20 % of GGBFS. This is because when the particles of GGBFS is in excess in the mixture, there is insufficient free calcium hydroxide which contribute to the hydraulic reactions with GGBFS particles. However, the rest of this particles remain inactive and do not contribute strength.

Flexural strength evaluation

Flexural strength testing was carried out for different cement/GGBFS mortars mixtures cured during 3, 7, 28 and 90 days of hydrations ages. As seen in Figure 6, the three considered parameters have significant effect on the flexural strength values. When the hydration ages of the samples increase, the flexural strength enhanced for all specimens. At 3 to 90 days of hydration age, the values of flexural strength increase from 3.31 to 9.43 MPa for specimen containing 30 % of GGBFS and 0.5 of w/b ratio. In addition, the results indicate that there is slight difference in the global trend of the flexural strength properties compared to the obtained compressive strength for mortars

with 0.35 and 0.4 of w/b ratios. The flexural strength values of the specimens cured at early ages of 3 and 7 days of hydration ages, were also certainly lowest. Moreover, these values increase at 28 days of hydration ages of mortars with different amount of GGBFS contents and the results appear that the optimal replacement level of cement with GGBFS strongly depends with the hydration age. Hence, the optimal amount of GGBFS addition is 20 % for mortars with both w/b ratios and hydration ages of 28 and 90 days. As mentioned previously, this is because at this concentration of GGBFS, the pozzolanic effect occurred in mortar lead to the formation of cement hydration and shorten stiffening time, which improves the flexural load materials and decreasing crack propagation. For the specimens with 0.45 and 0.5 of w/b ratios, the incorporation of GGBFS have no effect on the flexural strength properties of mixtures mortars. For the samples without and with 30 % of GGBFS, cured at 90 days of hydration ages and with 0.5 of w/b ratio, the values decrease slightly from 10.71 to 9.43 MPa, respectively. This loss of the performance of flexural strength values is mainly due to the characteristics of cement/GGBFS mixtures mortars at these experimental conditions. In the other hand, it appears from the results indicated in Figure 6 that is an effect on the variation of w/b and GGBFS additions at early ages and at 90 days of hydration ages. As a

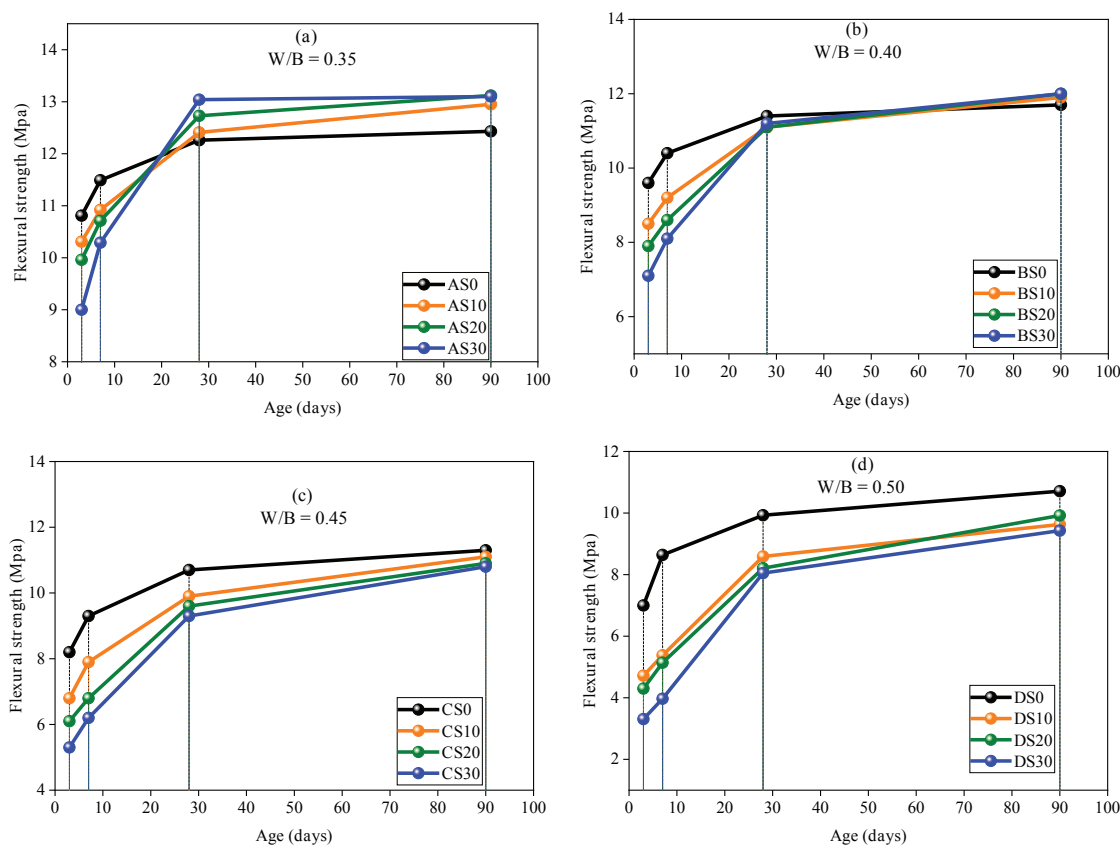


Figure 6. Flexural strength versus hydration age, GGBFS content and water-to-cement ratio from (a) to (d).

result, the flexural strength decreases 35.24 % when w/b ratio increase from 0.35 to 0.5 for mortars without GGBFS contents, and the flexural strength decreases 55.5 % for mortars with optimal amount of GGBFS. The same tendency is observed at 90 days of hydration age, 13.59 and 28.12 % for mortars without and with optimal amount of GGBFS.

Figure 7 translates the frequency histograms of experimental results obtained for flexural strength test of 64 samples of GGBFS-cement mortars. The findings of this

properties varied from 3 to 13 MPa with median of 9.44 MPa and low value of standard deviation of 2.46 MPa.

In the other hand, the correlation between the results of flexural and compressive strength is established in Figure 8, and can be expressed as indicated in equation (4).

$$F_f = -0.0018 (F_c)^2 + 0.332 F_c - 2.1587 \quad (4)$$

where F_f indicates the flexural strength and F_c presents the compressive strength.

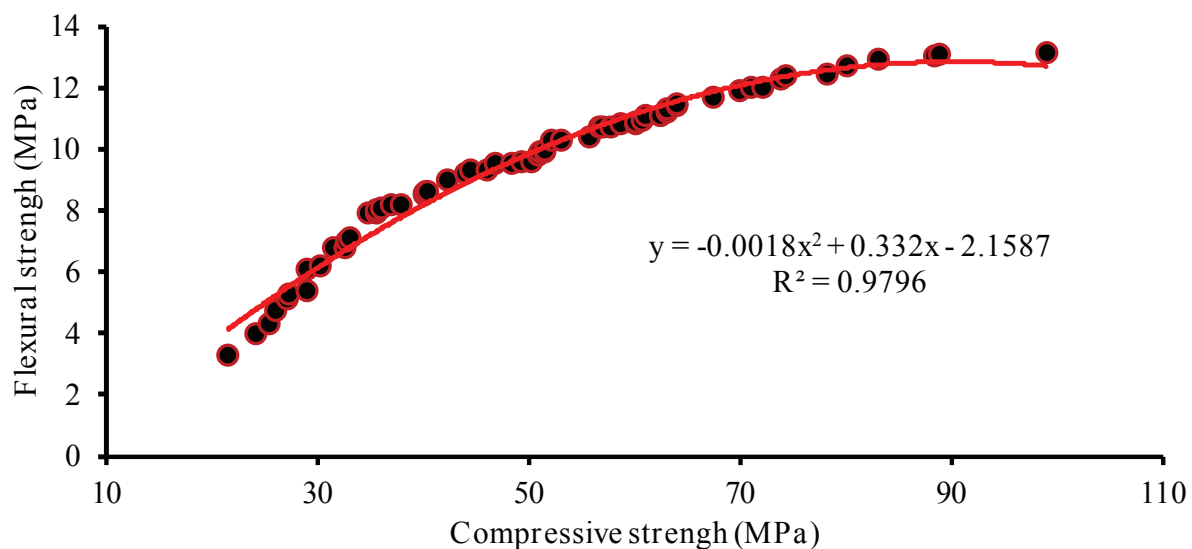


Figure 8. Flexural strength as function of compressive strength results.

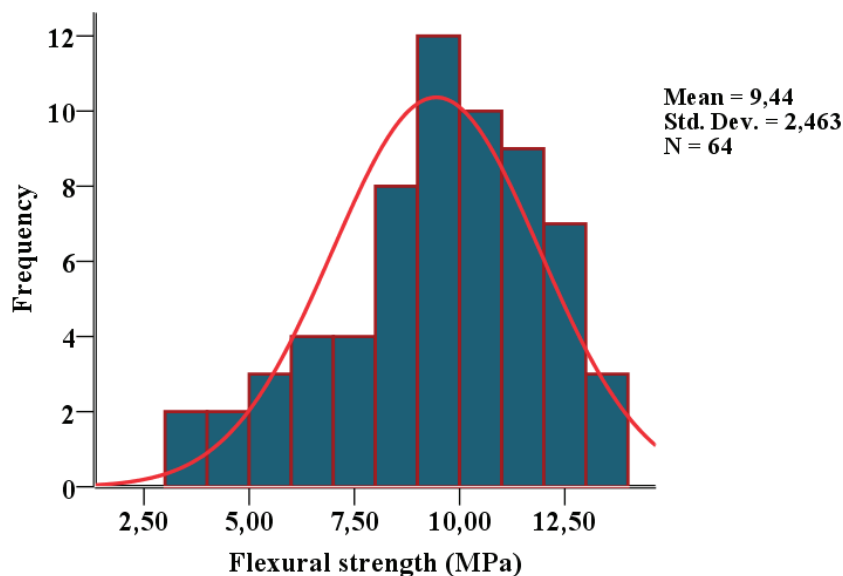


Figure 7. Frequency histogram of flexural strength results.

Regression Analysis

MLR models

The MLR analysis is one of the statistical methods usually applied to study the relation existing between the dependent variable, named endogenous, and different independent variables, named exogenous, which are the origin of the performance level of the dependent variable. Indeed, when this statistical test is used for the prediction model, the main objective is to explain the correlation existing between the experimental results and to describe the variation of the dependent variable as a function of the independent variables. According to the obtained results in this work, the correlation has been achieved between the dependent variables (flexural and compressive strength) and the independent variables (GGBFS contents, hydration age and w/b ratios). The following formulas present the mathematical equations of the obtained MLR model for the prediction of the compressive and flexural strengths of cement/GGBFS mortars, Eq. 5 and 6, respectively.

$$F_c = 44.812 + 0.300 (\text{Hydration age}) - 24.604 (\text{GGBFS content}) + 1.045 \text{ w/b} \quad (5)$$

$$F_f = 21.101 + 0.041 (\text{Hydration age}) - 4.604 (\text{GGBFS content}) - 26.401 \text{ w/b} \quad (6)$$

With F_c and F_f are the compressive and flexural strengths, respectively.

The sign and the values of each coefficient reflects the scale adopted, as indicated in the Eq.5, the compressive strength values increase with increasing of hydration ages and w/b ratios, but the high content of GGBFS involves the decreasing of compressive strength which is in accordance with the low optimal amount of GGBFS (20 mass%). The same results are obtained in the Eq. 6 for the hydration ages and GGBFS content, but is not the same for w/b ratios which decrease the flexural strength values with its increasing.

Model validation

In this analysis, the main objective is to determine the ability to express the experimental results obtained by the mechanical measurements and the results deduced using the two mathematical models translated using the values of correlation and determination coefficients indicated R and R^2 , respectively. Moreover, the statistical analysis is performed in order to confirm the situation arises in which it

does not provide a significant ability to relate the real observations; this examination was achieved through the analysis of variance test (ANOVA).

Table 7 gives the values of different determined coefficients that can be analysis the statistical quality of the regressions models obtained for both compressive and flexural strengths. Indeed, this analysis gives the results obtained for different statistical parameters, like: coefficient of correlation (R), coefficient of determination (R^2), adjusted coefficient of determination (Adjusted R^2), the standard error of estimate, and the Durbin–Watson statistics parameter. The R values define the existence of the correlation between the studied variables. In this case, both obtained models for compressive and flexural strength have coefficients of correlations of 0.65 and 0.89, respectively, which are higher than 0.5. These results indicate clearly that there is an importance correlation occurred between the experimental data and the adequate models. In addition, these two models lead to the R^2 values of 0.43 and 0.80 for compressive and flexural strength models, respectively. This result concluded that the MLR analysis has more efficacy on the prediction of flexural strength than compressive strength properties. Previous studies indicated that the MLR method gives low values of R^2 in the prediction of compressive strength of cementitious materials [19, 38, 39]. The values of this coefficient generally express the fraction of variance of the dependent variable (Y) that can be described by the regression model, but its values slightly affected by the presence of more variables, it generally increases with increasing of the number of considering variables in the model [40]. Indeed, the results of this coefficient revealing that 43 and 80 % of the variability of both mechanical properties, compressive and flexural strength, can be explained by the three independents variables, hydration age, GGBFS content and w/b ratios. However, the remaining 57 and 20 % of compressive and flexural strength model are mainly described by other factors or experimental errors, respectively. In the case of the of MLR model obtained for compressive strength results, the low values of R^2 can be due the existing of any non-linear relationships or interactions that the MLR approach cannot be statistically interpreted. The standard errors are estimated of 14.026 and 1.24 for both compressive and flexural models.

In the other hand, the Durbin–Watson statistic is used to test the existence of auto-correlation between the independent variables of the regression models, and its values generally varied from 0 to 4 with a midpoint of 2 [41–43]. The obtained values in this work are less than 2 (Table 6), 0.93 and 1.74 for compressive and flexural models, respectively.

Table 7. Summary of the MLR models obtained for compressive and flexural strengths, F_c and F_f , respectively

Models	R	R^2	Adjusted R^2	Standard error of the estimate	Durbin- Watson
F_c	0.65	0.42	0.40	14.043	0.937
F_f	0.89	0,80	0.79	1.24	1.74

This result indicates clearly the existence of the auto-correlation between the three studied parameters of hydration age, GGBFS content and W/B ratios.

The analysis of variance test (ANOVA) is also investigated in this work for both developed models in order to study the contribution and the interaction of considered independent variables (Table 8). From this analysis, the values of the sums of squares estimated for compressive and flexural models are established to distinct the global variance in the response obtained by the considered parameters and measurement errors [44]. Moreover, the F-test was determined in order to examine the elimination of null hypothesis and for the determination of the effect of each considered parameter on the different characteristics of studied material [45, 46]. Indeed, the values of F obtained for both models are much greater than that for F critical. The values of Sig. or significance level assumed in this work is 5 % (α) and the calculated values for Sig. for two models

are less than this fixed level ($0.000 < 0.05$). These results concluded that the relationship between the three considered independent variables and their interactions are statistically significant and they are the main causes of the dependents variables of compressive and flexural strength.

The statistical results estimated for the two obtained models are summarized in Table 9 and 10. Indeed, the B column indicates in both tables the values of the non-standardized coefficients for each independents variable. These values explain the alteration endured by the dependent variable of compressive and flexural strength whenever the independent variables varied by one unit. Using these non-standardized coefficients, the MLR models of compressive and flexural strength were expressed as indicated in both equations 5 and 6, respectively. The standard errors associated with each coefficient are also presented in Tables 9 and 10. Moreover, the standardized regression coefficient (Beta) translate the importance of independent variables during the estimation

Table 8. ANOVA table obtained for multiple linear regression analysis of compressive (F_c) and flexural (F_f) strength models

Models		Sum of squares	Degrees of freedom (df)	Mean square	F	Sig.
F_c	Regression	8705.18	3	2901.99	14.715	0.00
	Residual	11832.67	60	197.21		
	Total	20538.64	63			
F_f	Regression	304.03	3	101.43	77.80	0.00
	Residual	78.15	60	1.30		
	Total	382.18	63			

Table 9. The values of the regression coefficients of compressive strength model

	Non-standardized coefficients		Standardized coefficients	Statistical t	Sig.	Collinearity	
	B	Standard error	Beta			Tolerance	VIF
Constant	44.81	3.36	/	13.33	0.00	/	/
Hydration age (days)	0.30	0.05	0.58	5.81	0.00	0.95	1.05
W/B	1.05	0.74	0.14	1.41	0.16	0.95	1.05
GGBFS mass%	-26.40	15.74	-0.17	-1.68	0.09	0.99	1.01

Table 10. Regression coefficients of flexural strength model

	Non-standardized coefficients		Standardized coefficients	Statistical t	Sig.	Collinearity	
	B	Standard error	Beta			Tolerance	VIF
Constant	21.10	1.12	/	18.88	0.00	/	/
Hydration age (days)	0.04	0.004	0.56	9.66	0.00	0.99	1.00
w/b	-28.77	2.55	-0.66	-11.27	0.00	1.00	1.00
GGBFS mass%	- 4.60	1.28	-0.21	-3.60	0.00	0.99	1.00

of the dependent variable values obtained with the mathematical model. According to the values of this coefficient which varies between -1 and 1, it can be compared the importance of different variables considered in this work for the estimation of the mechanical properties. For both compressive and flexural models, it appears that the hydration age has a higher value of standardized coefficients than the two other variables of w/b ratios and GGBFS contents. This result involves that the hydration age has a significant effect on the estimation of compressive and flexural strength values, which is in accordance with literature review [12]. The two other independent variables have less effect on the assessment of mechanical properties. Indeed, for the compressive strength results, w/b ratios have more effect than GGBFS content with standardized coefficients values of 0.13 and -0.17, respectively. In contrast, the values of standardized coefficients indicate for flexural strength results that the GGBFS content has more effect than w/b ratios, -0.22 and -0.66, respectively.

The t-values are generally calculated in order to compare the power of each independent variables on the estimation and the prediction of dependent variable. Thus, the obtained t-values are generally evaluated with the comparison of its values with critical value of t deduced from t Student distribution table, the estimated absolute of t-values should be greater than $t_{critical}$ (1.664). For flexural strength model, the t-values of the coefficients for all independent variables are greater than $t_{critical}$. Nevertheless, the w/b ratios have t-values less than $t_{critical}$ for compressive strength model. For 95 % confidence level, the significance values of the three

independent variables are less than 5% (0.00) for flexural strength model, which conclude that the hydration ages, w/b ratios and GGBFS content are mainly the cause of the dependent variable. In contrast, both w/b ratios and GGBFS have significance more than 5 % for compressive strength model, 0.19 and 0.09 respectively. This result indicates that these two independent variables have lower effect than hydration ages (Sig. = 0.00) in compressive strength estimation.

The diagnostic of collinearity occurred between variables can be tested using VIF. According to the literature review [47, 48], the values of VIF greater than 5 reveals that the mathematical model exhibits collinearity effects and significant variables are insignificant in the model. The value of this statistical parameter is calculated using the equation (7) and its values around of 1 indicates that there is no collinearity effects. In this case, based on the result indicated in Tables 9 and 10, the values of VIF of the three independent variables: hydration age, GGBFS content and w/b ratios are around the value of 1 and < 5 for both developed models of compressive and flexural strength, which involves that there is no risk of collinearity effects.

$$VIF_i = \frac{1}{1 - T_i} \quad (7)$$

Where T_i is the tolerances values of each independent variable i .

The residuals results are also expressed as function of GGBFS content for compressive and flexural strength results (Fig. 9). The results of this study indicate clearly the

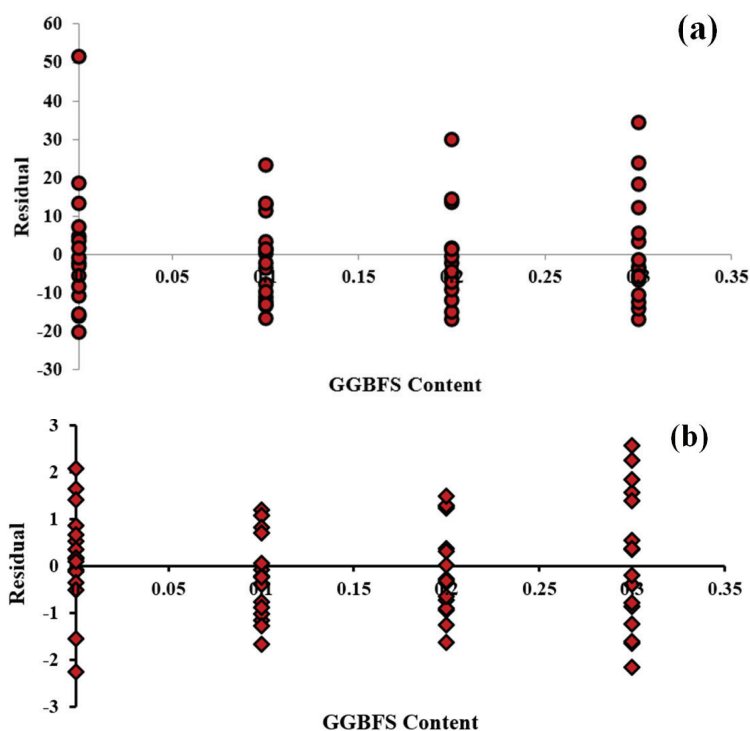


Figure 9. Residual results as function of (a) compressive and flexural values.

low range of residuals obtained for flexural strength analysis. The values are uniformly and symmetrically closed to zero, this is mainly due to the good significant of developed MLR model, which not the same for compressive strength values [48, 49].

In the other hand, the collinearity is checked using the correlation matrix between the independent variables (Table 11 and 12). The results of this analysis indicate that all values are higher than 0.7 for compressive and flexural strength models, due to the no collinearity existing between the three considered variables [48]. This conclusion is in accordance to the results obtained by VIF test. In addition, the correlation matrix indicates clearly that the GGBFS addition has more correlation with hydration age than w/b ratio.

The relationship occurred between the experimental results obtained for studied mechanical properties and their adequate predictive values are shown in Figures 10 and 11. Moreover, Figure 12 indicates a high correlation between predictive values of compressive strength and flexural strength estimated using the obtained models, Eq (5) and (6), respectively ($R^2 = 0.97$).

CONCLUSION

This work is conducted to study in the first the addition effect of ground granulated blast furnace slag on the mechanical properties of green cement mortar. Moreover, two predictive models are developed using the multiple linear regression analysis to predict the compressive and flexural strength of manufactured green cement mortars.

Table 11. Correlation matrix between independents variables of compressive strength model

	Hydration age (days)	w/b ratio	GGBFS mass%
Hydration age (days)	1		
w/b ratio	0.210703317	1	
GGBFS mass%	0.105414544	0.042543639	1

Table 12. Correlation matrix between independents variables of flexural strength model

	Hydration age (days)	w/b ratio	GGBFS mass%
Hydration age (days)	1		
w/b ratio	0.01231996	1	
GGBFS mass%	-0.036959879	0	1

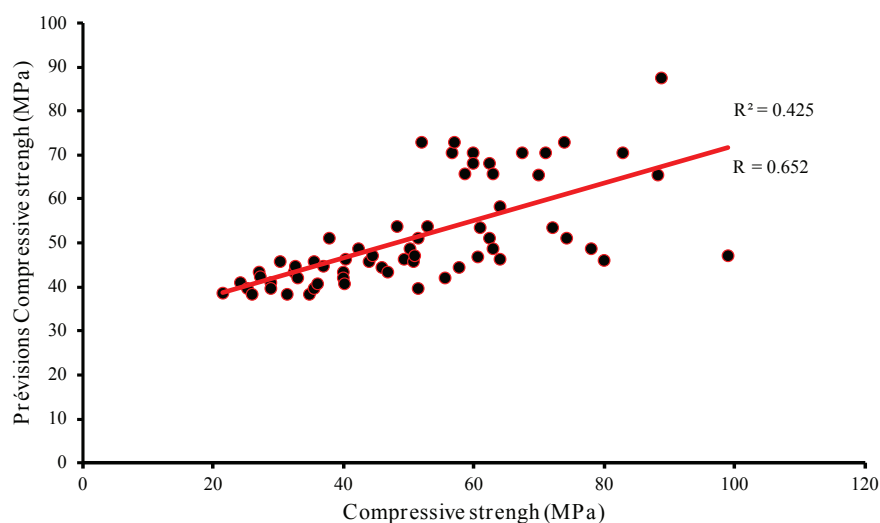


Figure 10. Predictive values versus of the obtained results of compressive strength.

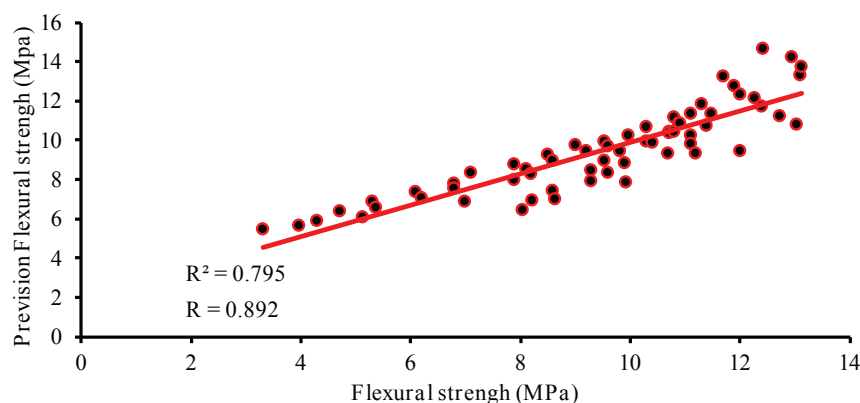


Figure 11. Predictive values versus obtained results of flexural strength.

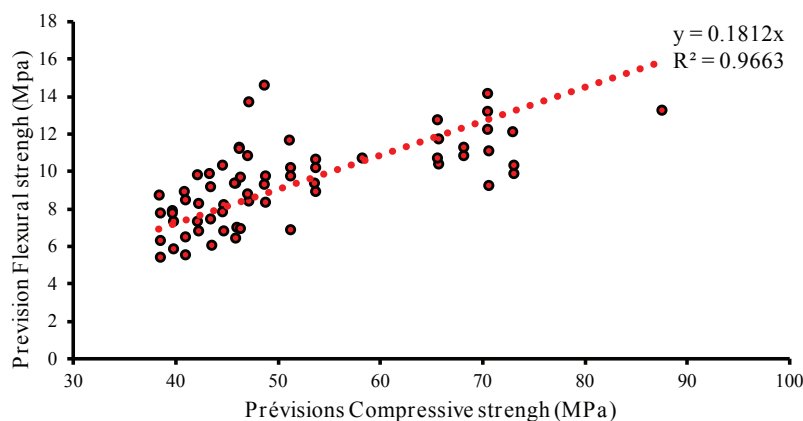


Figure 12. Relationship between previsions values of flexural and compressive strength.

Three quantitative variables are considered in this work of hydration ages, water/binder ratio and the concentration ground granulated blast furnace slag. Understanding the effect of these parameters on the final mechanical properties of different developed mortars, this study gives more economics solutions for the optimization of different necessary mixtures conducted in civil engineering applications and reduce a time for others experimental investigations by using the most statical results obtained by the multiple linear regression analysis.

The excremental results obtained via the compressive and flexural strength analysis concluded that the hydration age is the most important parameter that strongly affect the mechanical properties. In contrast, the GGBFS added as substitution of OPC improved the mechanical properties of cement mortar just at high hydration age of 28 and 90 days. As a result, the compressive strength increases from 73.01 to 88.89 MPa at for the samples with 0 and 20 % of GGBFS addition, 0.35 of w/b and 90 days of hydration age. The findings of these analyses conclude also that the optimal

amount of GGBFS content in cement mortar is 20 %, above this concentration there is a slight effect on the mechanical properties. For the samples mortars with 0.35 of w/b ration and 90 days of hydration age, the compressive and flexural strength decrease from 13.12 to 13.1 MPa and 88.89 to 88.33 MPa for 20 and 30 % of GGBFS content, respectively. Moreover, at different variation of w/b ratio, the GGBFS addition have significant effect just at high hydration ages, which is not the same for the flexural strength, this effect is also observed at early age.

Based to the most results obtained from the regression analysis, the values of R^2 conclude that the MLR method has more significant performance for the prediction of flexural strength properties than compressive strength of GGBFS-cement mortars, 0.8 and 0.42 values are obtained, respectively. Moreover, the compressive and flexural models present correlations coefficients values higher than 0.5 (0.65 and 0.89, respectively). These results translate the existing of high correlation between the experimental data and the models which lead to generate better results during

the prediction of both considered mechanical properties of GGBFS-cement mortars. Based to the statical parameters obtained from the multiple linear regression analysis, namely: sig. values, standardized coefficients and the values of the variation inflation factor, indicate clearly that the hydration ages have a significant effect on the prediction of both mechanical properties of GGBF-cement mortar, which is in accordance with the results obtained from the experimental tests. For the two others intend variables, the regression parameters indicate that w/b ratios have more effect than GGBFS content on the estimation of compressive strength values, which is note the same for the flexural strength values, the standardized regression coefficient increase from -0.66 to -0.22, respectively.

Refers to the different statical techniques previously developed for the prediction of the mechanical properties of cement materials, like the non-linear regression analysis and the machine learning of artificial neural networks (ANNs) and support vector machine (SVM), future research can be conducted using these methods for improvement of model's performance of compressive strength prediction and considering more independent variables like durability parameters and curing conditions of temperature and relative humidity.

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AUTHORSHIP CONTRIBUTIONS

Study conception and design, AH; data acquisition, KC and AH; analysis and interpretation of results, AH; draft manuscript preparation, AH; and manuscript review and editing, KC and AH.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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