



Optimization of High-Performance-Concrete properties containing fine recycled aggregates using mixture design modeling

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ABSTRACT. This investigation means to optimize the properties of High-Performance-Concrete (HPC) containing fine aggregates from concrete and brick wastes for different recycled aggregates substitution rates, using mixture design modeling.

To succeed this, the design of experiments (DOE) method was used. It is observed that slump, flexural and compressive strength of recycled concrete are significantly influenced by the content of natural sand (NS), recycled concrete aggregates (RCA) and recycled brick aggregates (RBA). The experimentally measured responses were successfully studied to develop a polynomial model, which represents slump, flexural strength and compressive strength at 7 day and 28 day of HPC. The significance and accuracy of the model was confirmed by statistical analysis and experimental verification. Under optimal conditions, the maximum desirability is 0.65, which can be obtained by using only recycled sands, i.e. RBA (9.5%) and RCA (90.5%), and no natural sand. The statistical results show that the proposed models are well correlated with the experimental data.

KEYWORDS. High performance concrete; Recycled aggregates; Mixture design modelling; Physico-mechanical properties; Optimization.



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INTRODUCTION

Several research studies have been carried out in many countries for the purpose of studying the possibility of recovering construction and demolition wastes and use them as aggregates in new types of concrete [1-8].

The recycling of construction waste as aggregates plays an important role in protecting the environment. Since it allows, on one hand, to get rid of the debris resulting from the demolition of old buildings and / or from natural disasters, and on the other hand, to protect nature against the excessive exploitation of natural aggregate reserves. However, the problem of recycled aggregates from concrete and brick is the adhered mortar and its increased water absorption, which affected the properties of recycled concrete [9-10].

In Algeria, most of the concrete used is exclusively made with alluvial sand. It is worth acknowledging that many parts of the country suffer from a remarkable lack of good quality alluvial sand. In addition, environmental requirements, production costs, depletion of alluvial deposits and remoteness of construction sites with respect to these deposits are also factors that encourage practitioners to search other types of sand [11]. Currently, the use of high-performance concretes (HPCs), thanks to their high strength, offers good long-term durability to construction structures and allows saving up to 40% of materials [12-13]. For these reasons, the present work aims to investigate the effects of recycled sand from construction sites on the physico-mechanical properties of high performance concretes. For this purpose, two types of recycled materials were been studied, namely recycled brick aggregates (RBA) and recycled concrete aggregates (RCA).

Recently, design of experiments DOE method has attracted the attention of many researchers in the construction field; [14-17]. This statistical method allows for a good control of the process, while performing a minimum number of tests; it also helps to determine the impact of each parameter when acting separately and when interacting with other parameters. However, in the field of recycled concrete, just few studies have used it [18-21].

In this article, a 3-factor, 4-level network mixture design-model based on the experimental design methodology was been applied. The factors for studying mixture design are the proportions of the constituents of the mixture (NS, RBA and RCA), these constituents are independent of each other. Moreover, the level represents the degree of accuracy levels chosen (25%, 50%, 75% and 100% in this study). The results obtained from the experimental tests and statistical analysis are presented as indicated by their substitution rates. So as to correctly valorise the incorporation of the aggregates of crushed brick and concrete, and to choose the most efficient optimal couples in the fresh and hardened states of concrete. It was decided to assess their impacts on the slump, the flexural and compressive strengths of concrete, at 7 and 28 days, in the form of a ternary iso-response diagram. The developed models were then compared with regard to their capacity to predict the intended responses, by analysing the coefficient of determination (R^2), adjusted coefficient of determination (R^2 adj), root mean square error (RMSE), residual variance (p -values < 0.05) and the graph of residuals according to the expected responses. To the best of knowledge, this is the first report using the modelling approach for mixture design with several statistical parameters, in forecasting the physical and mechanical properties of high performance concretes (HPCs) including recycled sand.

INVESTIGATED MATERIALS

Aggregates

Three types of fine aggregates were then selected:

- The natural sand (NS) used is an alluvial sand, with nominal size of 4 mm; the sand was dried at 105°C.
- Two type of recycled fine aggregates (sands) were used in this research. The recycled concrete aggregates RCA 0/4 and the recycled brick aggregates RBA 0/4 was obtained by crushing an ordinary concrete and bricks respectively, using a jaw crusher. Both RCA and RBA were dried at 105°C.

Two fraction size (4/8 and 8/16 mm) of natural coarse aggregates (NCA) were used. The NCA are a crushed limestone obtained from a local quarry in Algeria.

The physical properties of fine and coarse aggregates are shown in Tab. 1. The grain size curves are plotted according to the recommendations of standard NF EN 933-1; they are shown in the Fig. 1.

Cement

The cement used is of type CEMI 52.5 N, produced by the local Cement Plant in Algeria, with a fineness of 3461 cm^2/g and density of 3150 kg/m^3 was used in accordance with Standard EN 196-3 and 6.



Adjuvant

The adjuvant used is a new generation high-water-reducing superplasticizer of the MEDAFLOW 145 type. It is a solution of polycarboxylates, 31% dry extract, light pitch color, and pH between 5 and 6.

Silica fume

The apparent density of silica fume is 650 (kg/m³), the actual density is 2240 (kg/m³) and its Blaine specific surface is 23000 (cm²/g). Tab. 2 presented the chemical compositions of cement and silica fume (SF).

Type of Aggregate	Norme	Fine aggregates			Coarse aggregates	
		NS	RCA	RBA	NCA 4/8	NCA 8/16
Characteristics	/	NS	RCA	RBA	NCA 4/8	NCA 8/16
Fineness modulus	NF EN 12620	3.51	4.51	3.53	-	-
Absolute density (g/cm ³)	NF EN 1097-6	2.68	2.57	2.32	2.55	2.62
Apparent density (g/cm ³)	NF EN 1097-6	1.53	1.131	1.23	1.19	1.60
Sand equivalent (%)	NF EN 933-8	75.89	75.93	88.22	-	-
Compactness (%)	NF P 18-555	58	50.93	40.46	-	-
Water absorption (%)	NF EN 1097-6	1	8	14	0.04	0.03

Table 1: Physical and mechanical characteristics of fine and coarse aggregates.

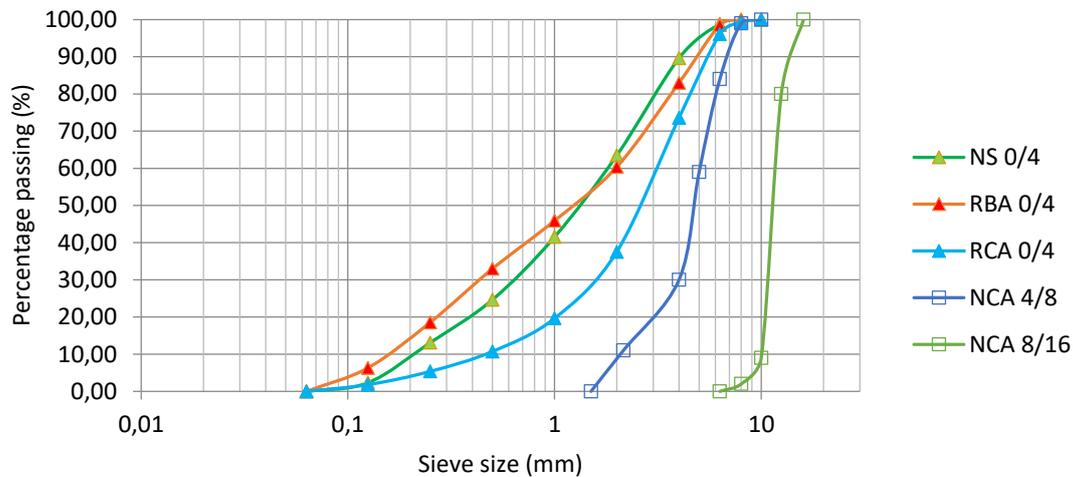


Figure 1: Grading curves of fine and coarse aggregates used.

The samples	SiO ₂ %	Al ₂ O ₃ %	Fe ₂ O ₃ %	CaO %	MgO %	SO ₃ %	Na ₂ O %	K ₂ O %	P.A.F. %
Cement (C)	21.70	4.27	4.83	64.11	1.35	1.59	0.08	0.32	0.99
Silica Fume (SF)	93.17	0.60	1.25	1.40	1.02	2.30	1.00	-	-

Table 2: Chemical compositions of the constituents.

SAMPLE PREPARATION METHOD

The formulation of High-performance concretes (HPCs) is based on the composition method developed by Aïtcin at the University of Sherbrooke [12]. A control concrete HPC 15 (CC) was prepared with natural aggregates, crushed gravel and alluvial sand (NCA 4/8, NCA 8/16 and NS).

The replacement of natural sand by recycled one, was done by replacing a percentage of NS by its equivalent volume of RBA and RCA. Only recycled sands were pre-wetted, for a period of 24 h before mixing, in order to avoid the possible absorption of mixing water by recycled aggregates [22]. They were then introduced into the mixer on a saturated-surface dry state; the other aggregates were used in their natural condition. Fig. 2 shows concrete composition for fifteen HPCs with various compositions (natural sand/ recycled sand).

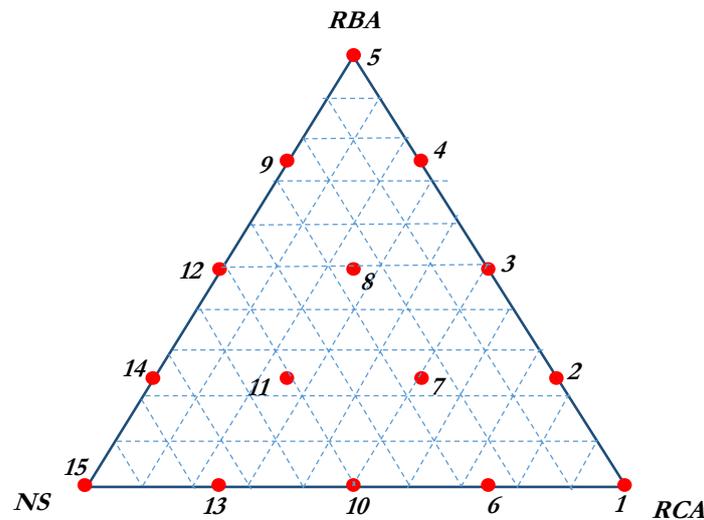


Figure 2: Representation of the triangular network with 15 combinations (15 tests).

The present work is expected to deal with a mixed-level design with 3 factors, i.e. natural sand (NS 0/4), and the two type of recycled fine aggregates, i.e. recycled brick aggregates RBA and recycled concrete aggregates RCA, taken in mass proportions; their sum must be equal to unity, with 75% substitution of alluvial sand. A constraint was put on the proportion of one-constituent (substitution of NS sand does not exceed 75 % in this case); a coding of the proportions was required. By considering, the remaining quantity that represents the unit, and the proportions of the points of experiments was deduced from the classic mixture design (Tab. 3).

It is worth noting that these factors are dependent on each other. The experimental domain must therefore satisfy the following condition:

$$\%NS + \%RBA + \%RCA = 100\% \quad (1)$$

A second-order polynomial model was used with three non-independent variables. The proportions of these factors are presented in Fig. 2.

TEST METHODS

The experimental program aimed to perform three physico-mechanical characterization tests: workability, compressive strength and flexural strength at 7 and 28 days. The workability tests were carried out by measuring the slump using the Abrams slump cone test. For this, the concrete was introduced into a standardized conical mold in accordance with the LCPC technique and in conformity with Standard NF EN 12350-2. It is worth indicating that the Abrams cone test is very simple to perform, rapid and relatively reliable.



On the other hand, the mechanical characterization was accomplished once the compressive and flexural strengths were measured at 7 and 28 days. The mechanical behavior of all the HPC mixtures was investigated in simple bending (3 points) and uniaxial compression on prismatic test specimens of dimensions (70x70x280 mm³). Moreover, three samples were tested, at each deadline, in simple bending on the bending frame of a Matest press with a maximum capacity of 25 kN. It should be noted that the change rate was set at 0.05 ± 0.01 MPa/s until failure, in accordance with the recommendations of standard NF P 18-407. The six half-test pieces resulting from bending failure were then subjected to uniaxial compression on the compression frame of a double-quadrant Controls brand press that has a maximum capacity of 200 kN, at a loading speed of 0.5 kN/s. The specimens were cured in water until the age of testing.

Mixture	Cement (kg/m ³)	Silica (kg/m ³)	NS (kg/m ³)	RBA (kg/m ³)	RCA (kg/m ³)	NCA 4/8 (kg/m ³)	NCA 8/16 (kg/m ³)	W (l/m ³)	W/C	Sp (L)
HPC1			182.70	0	532.32					
HPC2			182.70	120.05	399.24					
HPC3			182.70	240.10	266.16					
HPC4			182.70	360.15	133.08					
HPC5			182.70	480.20	0					
HPC6			321.16	0	399.24					
HPC7			321.16	120.05	266.16					
HPC8	450	50	321.16	240.10	133.08	273	777	150	0.3	6
HPC9			321.16	360.15	0					
HPC10			459.61	0	266.16					
HPC11			459.61	120.05	133.08					
HPC12			459.61	240.10	0					
HPC13			598.07	0.00	133.08					
HPC14			598.07	120.05	0					
HPC15			736.53	0	0					

Table 3: Mixture proportions for 1 m³ of concrete [kg/m³].

RESULTS AND DISCUSSION

According to the mixture design modelling, the responses as a function of the substitution rate for the three factors, i.e. NS, RBA and RCA. Which can be fully exploited in the development of the mathematical models and predict the properties of concrete mixtures (slump, compressive strength and flexural strength) for different parameters process values. These models make it easier to assess the effect of each factor separately, and in combination with the other factors. Tab. 4 depicts the results of the experimental characterization tests carried out in the laboratory; these results were obtained on the basis of the developed mixture design.

Effect of RCA and RBA on Slump

The measured slump changed from very plastic workability to plastic workability, for the different substitution rates of recycled sands.



Mixture	S (cm)	CS at 7 d (MPa)	CS at 28 d (MPa)	FS at 7 d (MPa)	FS at 28 d (MPa)
HPC1	18	58.76	82.54	7.40	12.13
HPC2	16.5	55.52	82.8	8.02	11.37
HPC3	13	52.07	81.72	7.75	11.52
HPC4	9	51.6	81.83	7.97	11.58
HPC5	6	46.88	77.1	7.55	11.53
HPC6	14	54.97	76.45	7.52	10.17
HPC7	10	52.4	78.14	7.74	10.29
HPC8	8	47.32	77.1	7.33	10.3
HPC9	7	45.49	75	7.17	10.72
HPC10	9	50.35	72.1	7.72	9.97
HPC11	8	50.22	74	7.42	10.87
HPC12	8	43.83	74.26	7.07	10.91
HPC13	9	55.33	71.84	8.21	10.86
HPC14	10	53.55	76.3	7.62	11.63
HPC15	16	63.2	80.24	8.75	12.55

Table 4: Experimental results of characterization tests.

Summary of Adjustment	
R ²	0.955131
R ² adjusted	0.930203
Root of the mean squared error	0.994628
Average response	10.76667
Observations (or weighted sums)	15

Table 5: Model estimation parameters for the slump under consideration

The concrete slump values were measured during the tests, which were compared with the results predicted by the generated model. The analyses of statistical parameters presented in Tab. 5 and Fig. 3(a) indicate that the Eq. (2) represent adequately the actual relationship between the independent variables and the responses. The ANOVA results for the slump show P-value < 0.0001 (Fig. 3(a)), which implies that the R² and adjusted coefficients (R² adj) were calculated to check the adequacy and fitness of the model. The values of (R²) and (R² adj) are close to 1, which implies also, that there are excellent correlations between the predicted and experimental models (Fig. 3(a)). The mathematical model used in the slump test is given by the following equation:

$$S(cm) = 15.064285714 \times NS + 6.2071428571 \times RBA + 19.171428571 \times RCA + \\ + NS \times (RBA \times -11.71428571) + NS \times (RCA \times -31.85714286) + RBA \times (RCA \times 0.1428751429) \quad (2)$$

This model, as expressed by Eq. (2), allows observing that the slump value is strongly conditioned by the increase in the mass proportion of RCA first, and then by the proportioning of NS and RBA. It is worth mentioning that the slump increase is mainly attributed to the physical behavior of RCA fines. Therefore, increasing the RCA content could result in a significant growth in workability values. It is widely acknowledged that sands from demolition concrete are rich in fines, and can therefore be used to significantly increase the workability of concrete. Moreover, it should be noted that the couples of factors (NS*RBA, NS*RCA and RBA*RCA) in the polynomial have negative effects. This may be assigned to the high quantity of fines which were responsible for the higher water demand. Indeed, when the content of recycled binary mixtures increases, the quantity of water required for wetting the entire surface of grains gets higher; this leads to slump decline in the manufactured concretes.

Furthermore, the iso-response curves of slump for high performance concretes (HPCs) are function to the percentage of substitution of the three types of sand are depicted in Fig. 3(b). which suggests that the existence of recycled aggregates reduces the workability of concrete in the fresh state, particularly for RBA proportions greater than 75%, i.e. 56.25% of the total sand mass, with a small percentage of RCA with respect to reference concrete (HPC15). Whereas, it is noted that demolished waste concrete fines significantly improve the workability of concrete, especially for RCA dosages greater than 75%, i.e. HPC2 and HPC6 which exhibit the highest slump values, i.e. 16.5cm and 14 cm, respectively, in comparison with the other types of concrete under study.

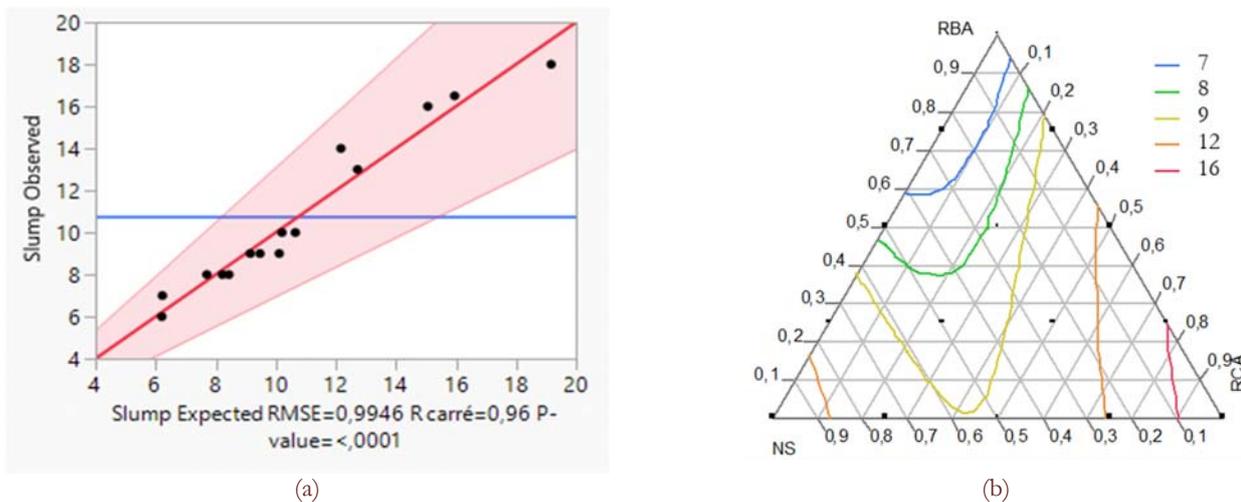


Figure 3: (a) Graphical representation of observed and predicted slump for the 15 tests, (b) Iso-response curves of slump of HPCs as function of substitution rates of the three types of sand (NS, RBA, RCA).

Effect of RCA and RBA on compressive and flexural strength

Mechanical characterization was carried out using compressive and flexural strength measurements to assess the effect of RCA and RBA recycled aggregates.

	Summary of Adjustment	
	CS at 7 d	CS at 28 d
R ²	0.940175	0.942657
R ² adjusted	0.906939	0.9108
Root of the mean squared error	1.566473	1.099557
Average response	52.09933	77.448
Observations (or weighted sums)	15	15

Table 6: Compressive strength model parameter estimates (CS at 7 d and CS at 28 d), Summary of Adjustment.



Summary of Adjustment		
	FS at 7 d	FS at 28 d
R ²	0.938866	0.922873
R ² adjusted	0.904902	0.880024
Root of the mean squared error	0.132442	0.259156
Average response	7.682667	11.09333
Observations (or weighted sums)	15	15

Table 7: Flexural strength model parameter estimates (FS at 7 d and FS at 28 d), Summary of Adjustment.

As clearly indicated in Tabs. 6-7, the models simulated show a good regression model with a large value of the correlation coefficients i.e R² = 0.9401, 0.9426, 0.9388 and 0.9228 for CS at 7 d, CS at 28 d, FS at 7 d and FS at 28 d, respectively. The results obtained from experimental trials using mixture design models for CS at 7d and CS at 28d have been predicted by using the Eqns. (3) – (4):

$$CS\ at\ 7\ d\ (MPa) = 63.055286 \times NS + 47.311714 \times RBA + 58.871714 \times RCA + NS \times (RBA \times -36.04857) + NS \times (RCA \times -34.10571) + RBA \times (RCA \times 1.1371429) \quad (3)$$

$$CS\ at\ 28\ d\ (MPa) = 79.258 \times NS + 77.443714286 \times RBA + 82.763 \times RCA + NS \times (RBA \times -14.10857143) + NS \times (RCA \times -34.82) + RBA \times (RCA \times 10.951428571) \quad (4)$$

Based on these models, it can be noted that CS at 28 d is first conditioned by the RCA content, next by the increase in the NS content, then by the RBA content and finally by the coupled effect of the RBA * RCA. On the other hand, it was found that the effects of the couple NS * RBA and NS * RCA cause a reduction in the compressive strength. The experimental results obtained for the mechanical strength are compared with the expected responses given by the JMP7 [23] software, they are represented graphically in Fig. 4. The models developed were then compared with respect to their ability to predict the expected responses such as presented in Tabs. 6-7. And by analysing the graph of the residues of expected results. One can clearly assert that since the graphical representation of the residues in terms of the expected values (Fig. 5) has a random shape, the fluctuations of residues are relatively small and regular for CS and FS at 28 days. In both cases, the developed models exhibit a slight deviation, there is no information left to extract.

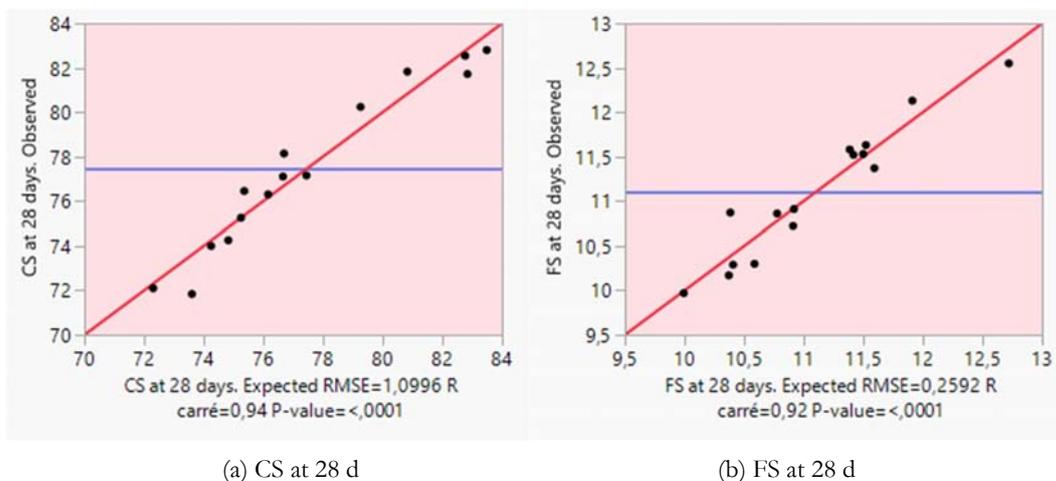
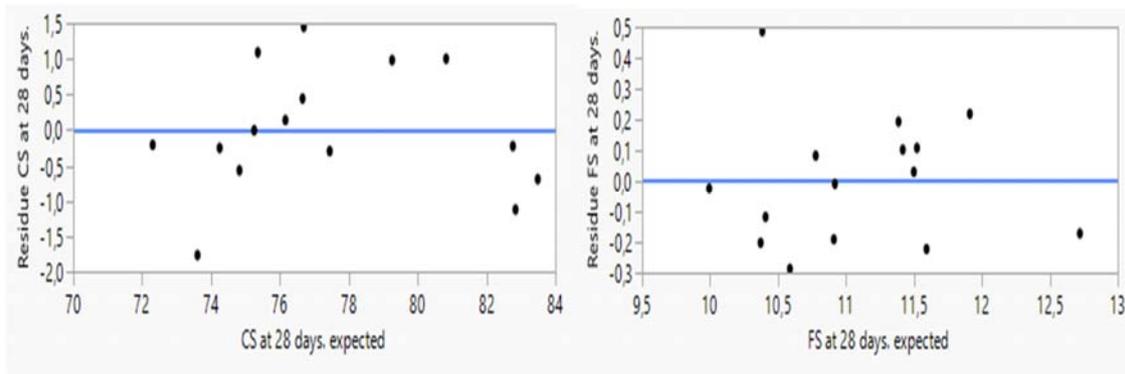


Figure 4: Graph representing the observed values as a function of the predicted values for the mechanical strength.



(a) CS at 28 d

(b) FS at 28 d

Figure 5: Graph perform the residues as a function of the predicted values at 28 days.

Figs. 6 and 7 clearly show that with experimental designs method, one obtains the maximum information with the minimum number of experiments.

The prediction profiler is used to study the impact of changes in study factors on predicted values. The curves in the profiler show the power of the impact of changes in each factor on responses. The prediction profiler of the compressive strength (CS) as a function of the substitution percentages for the three factors is shown in Fig. 8. This prediction profiler clearly indicates that the maximum of CS at 28 d can be achieved when the proportions of the three factors are 0% for NS, 25% for RBA and 75% for RCA; for these three substitution percentages, the compressive strength (CS) reaches a maximum value of 83.48 MPa, as shown in Fig. 8. Note that the incorporation of RCA above 75% slightly reduced the compressive strength. On the other hand, it is considerable to mention that RBA has a negative effect on the compressive strength CS in 28 days as it continuously generates lower responses than that of control concrete. This decrease can also be explained by the fact that recycled aggregates are less resistant, especially the brick sands, and therefore the mechanical strength of concrete should decrease.

According to the statistical model resulting from the response studied, it is clear that the resistance at 7 days has a very different trend on the ternary iso-response curve than the resistance at 28 days, as indicated by the coefficients of each factor and the negative influences of different coupled effects. If we are aiming for a high value of the compressive strength studied at 7 days, it will be necessary to choose a mixture with high RBA contents. If a high response of CS at 28 days desired, a mixture rich of NS and RCA will be chosen.

In conclusion, the factors do not influence by the same value at 7 and 28 days. RBA sand speeds the strength of concrete at 7 days while RCA gives an improved strength at 28 days.

The prediction Eqn. (5)-(6) shows the evolution of the flexural strengths at 7 and 28 days:

$$FS\ 7\ d\ (MPa) = 8.7431429 \times NS + 7.5938571 \times RBA + 7.4781429 \times RCA + NS \times (RBA \times -4.368571) + NS \times (RCA \times -1.425714) + RBA \times (RCA \times 1.7028571) \quad (5)$$

$$FS\ 28\ d\ (MPa) = 12.721428571 \times NS + 11.499285714 \times RBA + 11.911428571 \times RCA + NS \times (RBA \times -4.768571429) + NS \times (RCA \times -9.291428571) + RBA \times (RCA \times -1.151428571) \quad (6)$$

Furthermore, it is worth adding that the flexural strength FS at 7 days is also influenced by the percentages of the substitution of RBA and RCA. One may observe that after 7 days, the flexural strengths of HPC's with the substitution of RBA sand, achieved higher values of FS, than HPC's with RCA sand at the same percent of substations of these two sands presented in Eq. (5). This is mainly attributed to the pozzolanic reaction of fines from RBA brick waste sand i.e. calcined clay [24-26], which will have the effect of lowering the rate of portlandite (CH) and the production of new CSHs. This has led to better densification of the cement matrix.

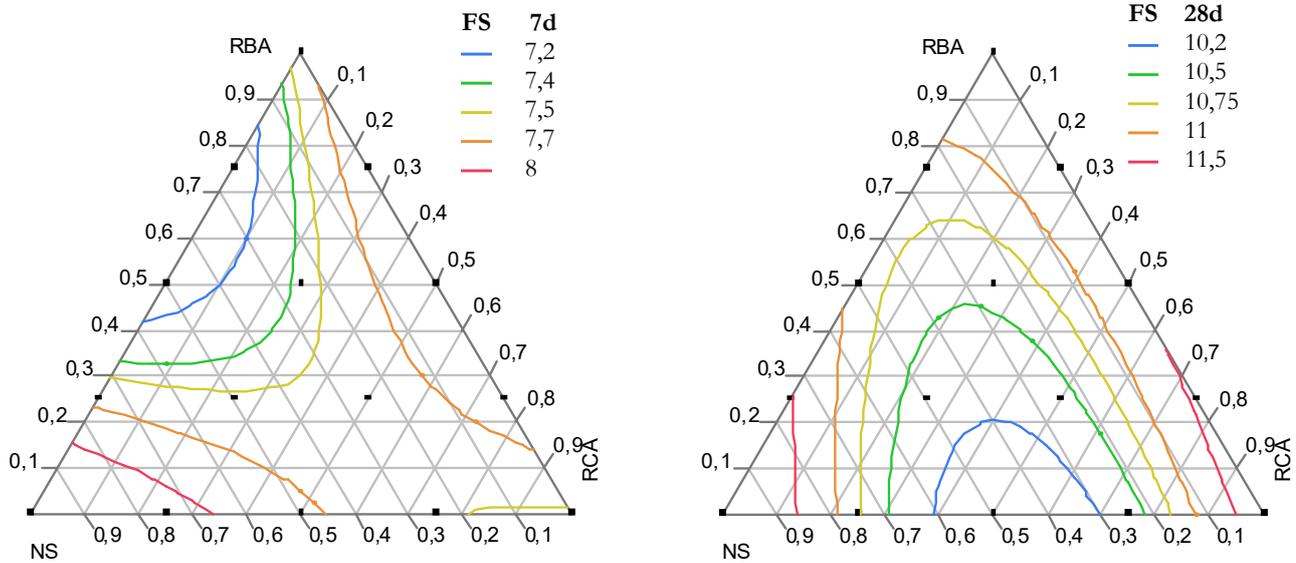


Figure 6: Iso-response curves for the flexural strength at 7 days and 28 days.

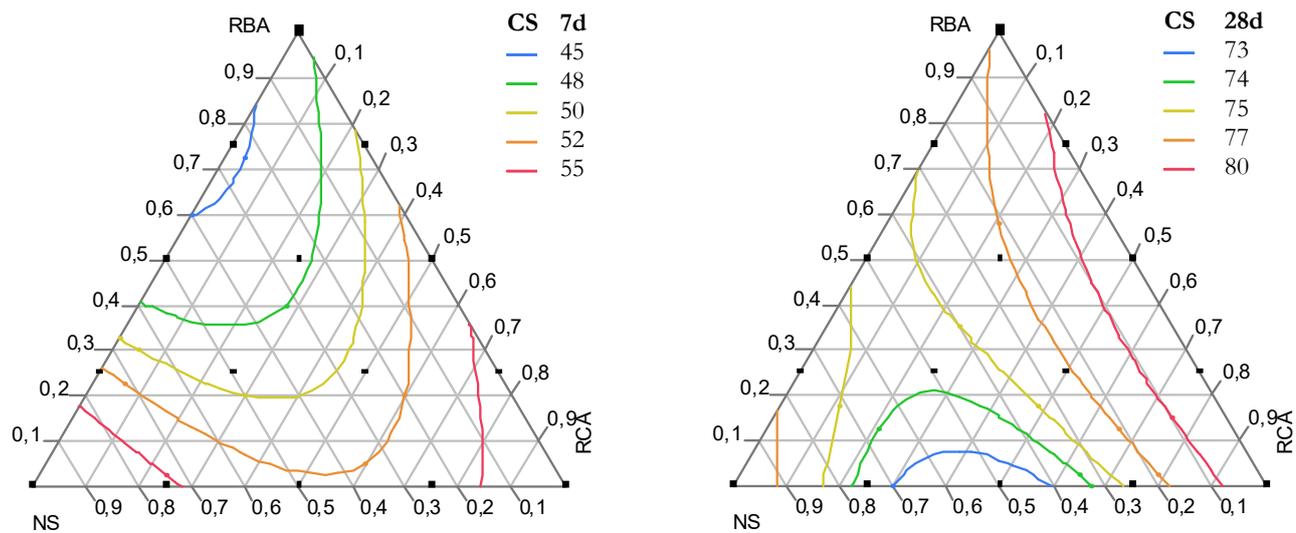


Figure 7: Iso-response curves for the compressive strength at 7 days and 28 days.

OPTIMIZATION

The search for the optimal proportions of fine recycled aggregates leading to the optimization of the recovery of fine recycled aggregates (RBA and RCA) having optimal responses, from previously established models, was done using the response profiler whose desirability value close to 1 corresponds to the maximum values of the physico-mechanical properties.

The optimization was performed using the desirability function which combines all the optimization targets into one (desirability).

According to this study, the maximum desirability is 0.65 (Prevision profiler) which can be reached for HPC without natural sand, by mixing the two recycled sands 9.5% of RBA and 90.5% of RCA. The optimized composition of the mixture gives: Slump=17.94 cm, FS 7d= 7.63MPa, FS 28d=11.77 MPa, CS 7d =57.86 MPa et CS 28d=83.20 MPa.

Furthermore, this optimization also showing that HPC can be produced with recycled sands from brick and concrete waste and makes it possible to achieve better properties to natural HPCs (HPC 15).

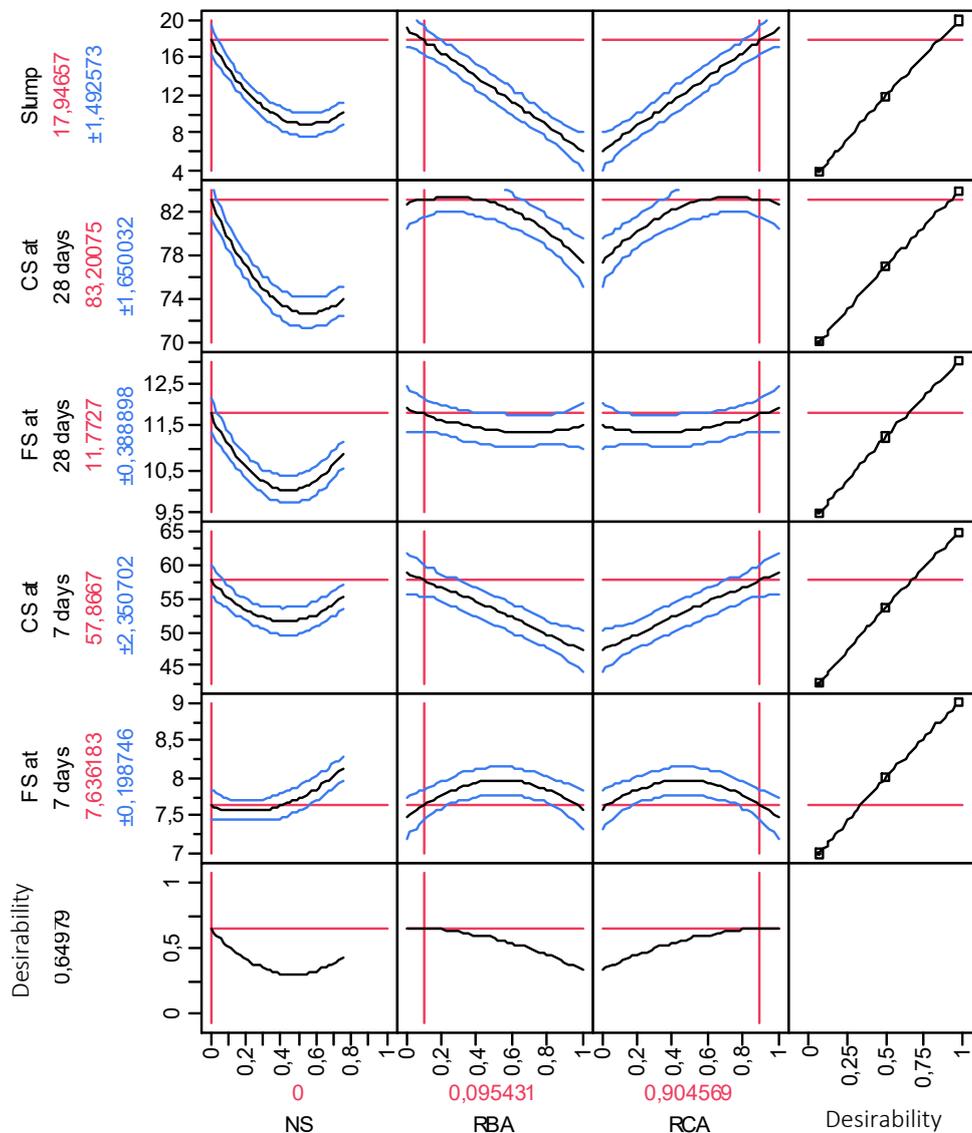


Figure 8: Prevision profiler for predicting optimal conditions for the formulation of recycled fine aggregate BHP.

CONCLUSIONS

The present research aimed mainly at assessing the effects of incorporating brick waste aggregates and concrete demolition waste aggregates on the physico-mechanical properties of concrete. Through experimental tests and analyses of each formulation, which contains different factors, with various substitution rates, and using the mixture design approach, it was found that a good agreement exists between the results of the mathematical models and those of the experimental tests, which validates the various considerable data on the effects of each of the recorded parameters.

In light of the outcomes got right now, the following ends could be drawn:

- The modelling of the mixture design method utilized right now has demonstrated to be a powerful procedure for considering the impacts of the three types of sand (NS 0/4, RBA 0/4 and RCA 0/4) in binary and ternary frameworks on the fresh and hardened concrete states. The advantage of modelling results studied using the



prediction equation is that it can evaluate all possible responses without carrying out all experiments. The measurements obtained during the tests allow developing polynomial models of prediction for the slump and mechanical strength of HPC's with fine recycled aggregates.

- It should also be noted that the compressive strength of the formulated concrete is comparable to that of control concrete. Moreover, it was found that following 28 days, the compressive strength (CS) reached a maximum value of 83.48 MPa with factors values of 25% RBA, and 75% RCA. And HPC's based on RBA sand presented greater values of flexural strength at 7 days than HPC's based on RCA sand, it was revealed that this is due to the RBA fines pozzolanic reaction and the production of new CSHs, which leads to better cement matrix densification.
- These findings demonstrate the robustness and usefulness of mixture design to model, predict and optimize the HPCs fine aggregate composition using RCA and RBA sands. It can therefore be concluded that HPC can be produced with recycled aggregates which has better properties.
- Substitution of natural aggregates with recycled aggregates for the production of the new concrete offers a new aggregate resource and allows saving natural materials.

It is worth mentioning that the physical and mechanical properties of the formulated concretes are encouraging. Moreover, the economic, environmental and technical aspects are also very interesting, which supports this initiative of recovering brick waste and concrete demolition waste to be used as building materials.

NOMENCLATURE

NS:	Natural Sand
RBA:	Recycled Brick Aggregates
RCA:	Recycled Concrete Aggregates
NCA:	Natural Coarse Aggregates
HPC:	High Performance Concrete
SF:	Silica Fume
Sp:	Superplasticizer
C:	Cement
(W/C):	(Water / Cement) ratio
S (cm):	Slump
CS at 7d:	Compressive Strength at 7 days.
CS at 28d:	Compressive Strength at 28 days.
FS at 7d:	Flexural Strength at 7 days.
FS at 28d:	Flexural Strength at 28 days.
DOE:	Design of Experiments.

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