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Article *in* Journal of Adhesion Science and Technology · February 2018

DOI: 10.1080/01694243.2018.1434032

Taylor & Francis
Taylor & Francis Group

Journal of Adhesion Science and Technology

ISSN: 0169-4243 (Print) 1568-5616 (Online) Journal homepage: http://www.tandfonline.com/loi/tast20

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To cite this article: Rebih Zaitri, Salim Guettala & Madani Bederina (2018): Physico-mechanical properties of mortars based on the addition of dune sand powder and the recycled fines using the mixture design modelling approach, Journal of Adhesion Science and Technology, DOI: 10.1080/01694243.2018.1434032

To link to this article: https://doi.org/10.1080/01694243.2018.1434032

Published online: 12 Feb 2018.

JOURNAL OF ADHESION SCIENCE AND TECHNOLOGY, 2018
https://doi.org/10.1080/01694243.2018.1434032

Physico-mechanical properties of mortars based on the addition of dune sand powder and the recycled fines using the mixture design modelling approach

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ABSTRACT

Physico-mechanical properties of mortars based on the addition of dune sand powder (DSP) and the recycled fines (RF) using the mixture design modelling approach were investigated. This experimental program aims to provide solutions and answers on the use of DSP and the recycled concrete waste in the form of fines for manufacture of the mortar having good properties. For this purpose, both additions are added by substitution of cement up to 25%. Through the results obtained, we have noticed the interest of modelling the response studied by a polynomial which is then able to calculate all the responses of the field of study without being obliged to make all the experiments. The obtained results showed that the introduction of DSP and RF in cement (by substitution) leads to a considerable improvement of mechanical strengths. The dosages of the three factors have optimum values (respectively around 66.66% of cement, 33.33% of DSP, 0% of RF in substituted volume of 112.5 kg of cement) for which the compressive strength (Cs) reaches a maximum value. Cs increases when the percentage of additions increases till an optimum (8.33% DSP, 8.33% RF), then decreases for larger percentages. One can observe that after 28 days, highest flexural strengths are that of mortars M7 and M9, with an optimum effect for the mortar M7. In addition, the modelling of the workability shows that the presence of DSP improves the workability of the mortars in the fresh state. Recycled fines have a negative effect on the flow time.

ARTICLE HISTORY
Received 27 September 2017
Revised 23 January 2018
Accepted 24 January 2018

KEYWORDS
Mortars; dune sand powder; recycled fines; workability; mechanical strength; mixture design approach

1. Introduction

Different mineral additions are currently being used more and more in concrete; they are used as addition or in substitution for part of the cement as supplementary cementing materials, for many reasons, either for economic reasons, either to improve certain properties of the fresh or hardened concrete, either for ecological reasons. We proceeded to the use of dune sand powder (DSP) and recycled fines (RF) (abundant materials, and therefore relatively inexpensive) as additives in the context of minimizing the cost of mortars. Demolition

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waste constitutes a major portion of total solid waste production in the world [1]. The research conducted by many researchers in concrete has clearly advised the possibility and feasibility of demolition waste recycling of the concrete it again appropriately as a cementitious addition. The use of fines resulting from the recycling of demolition concrete helps to limit the systematic use of natural resources, to reduce the area reserved for the storage of waste. This is included in a current issue of waste management. Cements with additions will not only reduce production costs but also to solve some environmental problems in addition to offering better performance to concrete [2], which can be achieved by using the DSP. Dune sand is a very abundant natural material in southern Algeria, the use of DSP as a mineral addition has been the subject of the recent experimental researches [2–7]. The results of these researches have shown that the DSP is capable of developing a pozzolanic reaction in a cementitious medium, thereby the analysis by X-ray diffraction highlighted the pozzolanic role of DSP (partial pozzolanic reactivity) [2,5–7]. Grinding the dune sand allows obtaining amorphous fine populations adsorbed at the surface of the crystalline particles (amorphization of the grain surface). This gives the DSP a pozzolanic character [2,5]. The introduction of the addition of the DSP in the cement production enables, in addition to the ecological and economic gain, an improvement in the physico-mechanical properties of mortars. Furthermore, and to carry out the composition of the mixture studied, we used a new technique of optimization (experimental plans method) that permits both to streamline the test program and to empirically model the responses obtained according to the study parameters as well [8]. Through a statistical approach, that latter allows driving a definite number of tests and results have capable of revealing the effect of each parameter studied separately and in interaction with other parameters. In this paper, we present the results obtained from experimental tests and the analysis of each modification made by the different additions used according to their substitution rates. In order to properly valorize the mineral additions used, we quantified their effects on the workability, the compressive and flexural strength. The required objective is to evaluate the physico-mechanical properties of mortars based on the addition of DSP and the RF using the mixture design modelling approach. This makes it possible to choose the optimal couples (DSP / RF) the most efficient, both in terms of mechanical strength that workability point of view. For this reason, and as it has already been reported, we use the theory of mixture design modelling that enables us to prioritize influential parameters and to quantify the effects.

2. Experiments and methods

2.1. Materials

The cement that was used is an ordinary Portland cement (CEM I) class 42.5 MPa; it from the cement factory of El Kharrouba (Tunis) and in accordance with Tunisian standards TS 47.01 [9] and TS 47.26 [10]. Fineness Blaine = 3300 cm^2/g and specific density = 3120 kg/m^3. The used water is drinking water having a temperature of 20 ± 2 °C. We used two different additions: the siliceous fines (dune sand powder (DSP)) obtained by finely grinding the dune sand from the region of Djelfa (Algeria), and recycled fines (RF) produced after sieving through a sieve 80 µm of the demolition waste of the concrete. The physical properties of used powders are shown in Table 1. Table 2 contains the chemical compositions of used powders. From a chemical stand point, the important observation to note is the presence

Table 1. Physical properties of used powders.

Properties	DSP	RF
Specific density (kg/m^3)	2790	2880
Fineness (cm^2/g)	4000	3890

Table 2. Chemical compositions of used powders (%).

Element	SiO_2	CaO	MgO	Al_2O_3	Fe_2O_3	LOI
DSP	86.04	6.63	0.08	1.35	0.86	5.00
RF	55.37	26.84	0.31	0.22	0.45	16.76

Note: LOI: Loss on ignition.

of a high percentage of silica SiO_2; is greater than 86%, and therefore the dune sand powder has siliceous characteristics. It is found that the recycled fines have silico-calcareous characteristics. The main elements are silica with a percentage that reaches 55.37% and the lime with a percentage that reaches 26.84%. The sand used (0/5 mm) is from the Djelfa region and of siliceous nature. The different physical properties of sand used are summarized in Table 3. The grading curve of sand is given in Figure 1.

2.2. Mixture design approach

The mixture design approach consists of statistical methods that can be used to better organize experimental tests [11]. It can be applied in many disciplines and in all industries where several factors (x_i) (in the case of mortars, the proportions of individual component materials) influence one or more properties, or responses (Y) (the fresh and hardened characteristics of the mortars). It is therefore very interesting to use this method when we have to study a function of type:

$$Y = f\left(x_i\right) \tag{1}$$

Indeed, when we use this technique, a maximum of information is obtained with a experiences minimum. To do this, we have to follow mathematical rules and adopt rigorous steps. There are many experimental plans suitable for all the cases which can be encountered by an experimenter [12]. This method is based on two main concepts, the experimental space and the mathematical modelling of studied variables. The studied factors are the proportions of components of the mixture [13]. However, these components are not independent of each other and the proportions of a mixture must sum to 100%. The percentage of the last component is imposed by the percentages of the first components. This is why the mixture plans are treated aside. The mixture plans are also characterized by many constraints that

Table 3. Physical properties of sand.

Properties	Result
Apparent density (kg/m^3)	1410
Specific density (kg/m^3)	2610
Sand equivalent (%)	77.13
Fineness modulus (FM)	2.57

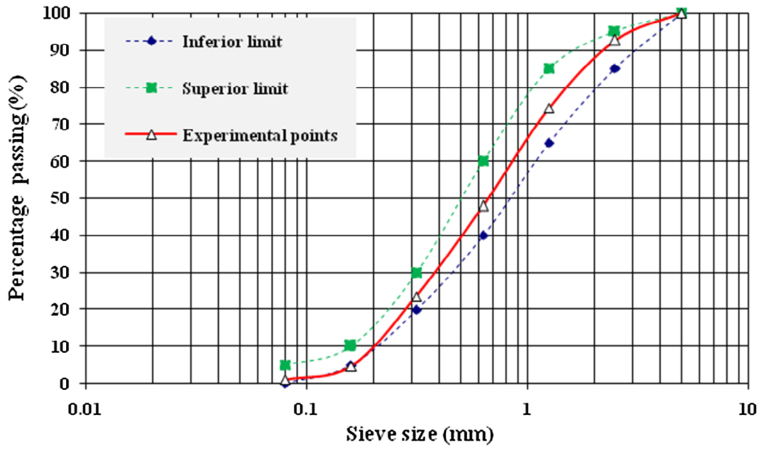


Figure 1. Grading curve of sand.

may influence the choice of the proportions of the constituents. For example, the concentration of a product must be at least *x* per-cent or the concentration may not exceed a given value. Based on these constraints, the planning study is modified and must be adapted to each case. If we denote by x_i the content of component i, the sum of the concentrations of all components of the mixture satisfies the relation:

$$\sum_{i=1}^{i=n} x_i = 100\% \tag{2}$$

If the sum of the concentrations of various constituents is brought back to the unit (1), the Equation (2) becomes:

$$\sum_{i=1}^{i=n} x_i = 1 \tag{3}$$

This relationship is called the fundamental constraint of mixtures. The geometrical representations of mixture designs are different from those used for conventional experimental designs and mathematical models are also profoundly modified.

2.3. Mixture proportions

Our experimental program aims to understand the role played by the various parameters separately (content of cement (C), content of dune sand powder (DSP) and content of recycled fines (RF)) on the properties of mortars. Thus, we have to consider a mixture design with three factors (C, DSP and RF) taken in mass proportions, whose sum is equal to unity with a substitution of cement up to 25% (112.5 kg of cement). This means that these factors are dependent on each other. The experimental field is constrained by the following equation:

$$C + DSP + RF = 1 \tag{4}$$

The number of experiments generated by the program is calculated by the following equation:

$$C_{q+m-1}^{m} = \frac{(q+m-1)!}{(m)!(q-1)!} \tag{5}$$

where (q) is the number of factors and (m) is the number of levels.

With three factors and three levels, a mixture design comprising 10 experiments was prepared in order to evaluate the influence of these factors on the properties of mortars. The model can be written under the form $Y = f(x_i)$ where the function (f) is a polynomial development of an order greater or lesser of xi, the order of the polynomial depends on the desired degree of precision. In this study, a third-order polynomial model was used with three non-independent variables (C, DSP and RF) and three levels. The model is expressed as:

$$Y = a_1 \times (C) + a_2 \times (DSP) + a_3 \times (RF) + a_4 \times (C.DSP) + a_5 \times (C.RF) + a_6 \times (DSP.RF) \tag{6}$$

where (Y) is the response and (a_1, a_2, a_3, a_4, a_5, a_6) are the model coefficients.

The model coefficients identification is required; they express the effect of the response to each factor and each interaction. Figure 2 shows the triangular lattice of the 10 studied combinations and the proportions of the experience factors generated by the software are shown in Table 4. In our case, the desired responses are the workability, the compressive and flexural strength. The obtained results of responses are then injected into the software (JMP7). They are represented by ternary diagrams connecting the components of the matrix (cement, DSP and RF) with the studied responses that highlighted the predominant matrix components. The same diagrams have also enabled us to optimize the composition of reference mortar. The basic composition is kept constant for all tests thereafter, except for the binder content which is composed of a ternary mixture (C, DSP and RF). The binder content, which is considered as ternary mixture, was developed based on these three components

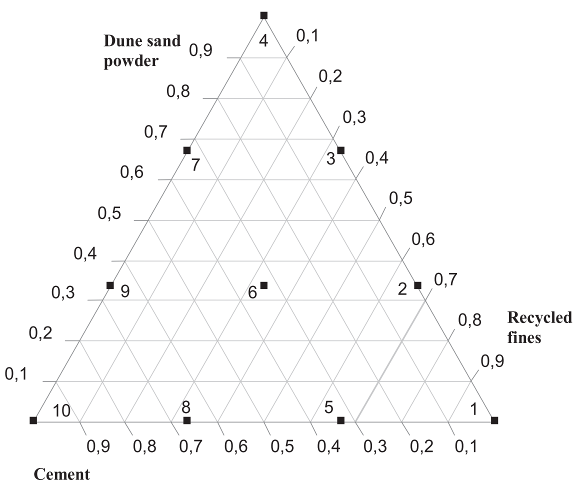


Figure 2. Triangular representation of the 10 combinations studied with three components.

Table 4. Factors proportions in the studied compositions.

N°	Cement	DSP	RF
1	0	0	1
2	0	0.33	0.66
3	0	0.66	0.33
4	0	1	0
5	0.33	0	0.66
6	0.33	0.33	0.33
7	0.33	0.66	0
8	0.66	0	0.33
9	0.66	0.33	0
10	1	0	0

Table 5. Different studied mixtures (kg/m^3).

Mixture code	Cement	DSP	RF
M1	337.5	0	112.5
M2	337.5	37.5	75
M3	337.5	75	37.5
M4	337.5	112.5	0
M5	375	0	75
M6	375	37.5	37.5
M7	375	75	0
M8	412.5	0	37.5
M9	412.5	37.5	0
M10	450	0	0
Water/binder ratio = 0.5			
Sand/binder ratio = 3			

for all studied compositions with proportions resulting from the use of statistical software JMP7. The different studied mixtures are summarized in Table 5.

2.4. Specimens preparation

The mixing was performed by means of a mortar mixer of 5 liters-capacity. A standard mixing according to European standard NF EN 196-1 was adopted for the elaboration of the different studied mortars while ensuring that the mixture is as homogeneous as possible. For the mechanical characterization, prismatic specimens of 40 × 40 × 160 mm were used. The filling of the molds is carried out in two layers. Each of the layers is set up by 30 shocks to promote the evacuation of air bubbles and then stitched to promote interlayer adhesion. After placing the mortar in the molds, the specimens were covered with plastic sheets and held at ambient laboratory conditions. After 24 h, all the test specimens were demolded and conserved in a water bath saturated with lime at a temperature 20 ± 1 °C during 28 days.

3. Results and discussion

The results of the 10 mixtures, statistically balanced with the three factors (C, DSP and RF) can fully be exploited in the development of mathematical models describing the effect of the type of addition on the properties of mortars. These models facilitate the assessment of the effect of each addition separately and in combination with another type of addition on the properties of mortars by using ternary diagrams with iso-response curves. Moreover, an analysis of variance allows the dissociation of the different studied effects starting from the variance of the measured response and allows us to see the contribution of factors on the variability of the response. The validity of the models can be tested by the statistical method based on the calculation of errors from the experiment and the model. The most suitable models have relatively high correlation coefficients. This finding shows a good correlation between the results obtained by simulations and the values predicted by the model found thereby. The results of characterization tests are presented in Table 6.

3.1. Workability modelling

The workability tests by flow time measurement were carried out using mortar maniabilimeter according to LCPC-technique defined by standard NFP 18-452 [14]. The simultaneous mass substitution of the cement by the three mineral additions generates a variation in the workability of the fresh mixture characterized by the flow of the mortars in the fresh state. The results obtained from the flow time during the tests are compared in Table 7 with the results expected by the JMP7 software. In Table 8, the model parameters estimates of studied response (flow time) are shown. The mathematical model retained for the flow time is:

$$\begin{aligned}\mathbf{Flow\ time}(s) &= 2.4891 \times \mathbf{C} + 2.2977 \times \mathbf{DSP} + 3.0191 \times \mathbf{RF} + \mathbf{C} \\ &\times (\mathbf{DSP} \times -4.2364) + \mathbf{C} \times (\mathbf{RF} \times 1.4079) + \mathbf{DSP} \times (\mathbf{RF} \times 0.0386)\end{aligned} \quad (7)$$

According the derived statistical model of workability, it is clear that the studied parameters have an influence on the flow time value as it is indicated by the coefficients of each parameter and give satisfactory values for workability. The results also show that the type and proportion of the three factors (C, DSP and RF) and their mixtures influence the workability of fresh mortars. From the model, we observe that the flow time is conditioned first by the increase of the dosage in RF, followed by the dosage in C and DSP, then by the various coupled effects. The workability values measured by the flow time of the various optimized mortars are represented in a graph which presents the observed values as a function of the expected values (see Figure 3) and in the form of ternary diagrams in Figure 4 which illustrates better the effects of the three studied factors. According to the analysis of the results found, it can be seen that the presence of the DSP improves the workability of the mortars in the fresh state especially for the dosages 33.33 and 66.66% (i.e. d: 8.33 and 16.66% of total mass of the cement) relative to the reference mortar (M10). This may be due to the great

Table 6. Results of characterization tests.

Mixture code	Time of flow measured (s)	Mechanical strength at 28 days (MPa)	
		Flexural strength	Compressive strength
M1	3.00	8.30	33.11
M2	2.84	9.01	29.24
M3	2.75	9.31	22.88
M4	2.25	8.90	25.60
M5	3.16	9.58	35.27
M6	2.18	9.78	34.35
M7	1.56	10.48	39.32
M8	3.03	9.65	38.84
M9	1.40	10.33	43.52
M10	2.50	8.64	36.62

Table 7. Comparison between the expected and measured results of flow time (s).

Mixture code	Time of flow measured	Time of flow expected
M1	3.00	3.01914285714286
M2	2.84	2.78723809523810
M3	2.75	2.54676190476190
M4	2.25	2.29771428571429
M5	3.16	3.15533333333333
M6	2.18	2.29200000000000
M7	1.56	1.42009523809524
M8	3.03	2.97866666666667
M9	1.40	1.48390476190476
M10	2.50	2.48914285714286

Table 8. Model parameters estimates of studied response (flow time).

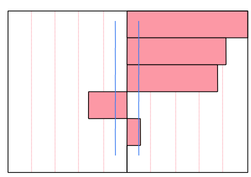
Summary of adjustment	
R^2	0.985711
R^2 adjusted	0.967849
Residual SD	0.108823
Average response	2.447
Comments (or weighted sums)	10

Estimates of coefficients

Term	Coeff.	SD	Ratio t	*p*-value
a1: (C)	2.4891429	0.102416	24.30	<0.0001*
a2: (DSP)	2.2977143	0.102416	22.44	<0.0001 *
a3: (RF)	3.0191429	0.102416	29.48	<0.0001 *
a 4: (C×DSP)	−4.236429	0.453376	−9.34	0.0007*
a5: (C×RF)	1.4078571	0.453376	3.11	0.0360*
a6: (DSP×RF)	0.0385714	0.453376	0.09	0.9363

Estimates of sorted coefficients

Term	Coeff.	SD	Ratio t	*p*-value
a1: (C)	3.0191429	0.102416	29.48	<0.0001 *
a2: (DSP)	2.4891429	0.102416	24.30	<0.0001 *
a3: (RF)	2.2977143	0.102416	22.44	<0.0001*
a 4: (C×DSP)	−4.236429	0.453376	−9.34	0.0007*
a5: (C×RF)	1.4078571	0.453376	3.11	0.0360*
a6: (DSP×RF)	0.0385714	0.453376	0.09	0.9363



Notes: R^2: correlation coefficient.
SD: standard deviation.
Coeff.: the estimated coefficient in the linear model.
p-value: is small enough to indicate very convincing significance. P-values are the probability of getting an even more extreme statistic given the true value being tested is at the hypothesized value, usually at zero.
*Marks the probability values validated by the used software.

fineness of the DSP used, so they fill the pores and release imprisoned water. In addition, the recycled fines have a negative effect on the flow time. This finding proves that the large quantity of RF rate significantly increases the demand of water. Indeed, the higher the filler content, the higher is the demand of water required to wet the entire surface area of grains [15]. We notice a flow time of about 3.16 s for the M5 (mortar with 66.66% of RF) which has a highest flow time compared to the other studied mortars. According to the profiler of flow time prediction (see Figure 5) which made it possible to establish curves having for purpose to facilitate interpretation and to allow a better analysis, it is observed that the

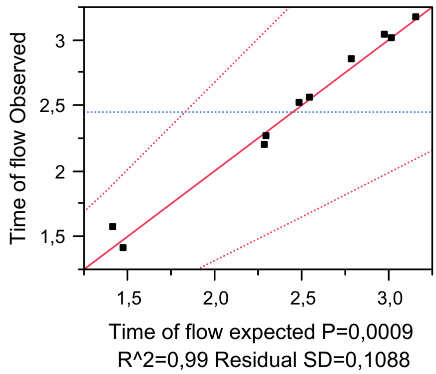


Figure 3. Graph of observed values as a function of expected flow time values.

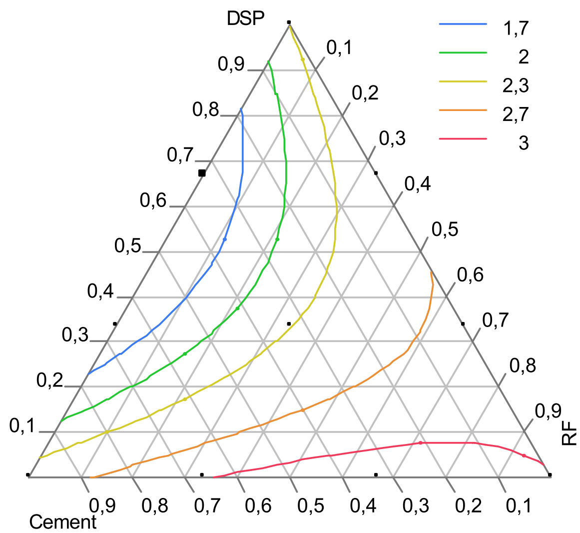


Figure 4. Iso-response curves of the workability of mortars measured by the flow time as function of cement, DSP and RF proportions.

presence of the DSP improves the workability of the mortars tested in the fresh state, in particular for the dosages of 60% cement, 40% DSP and 0% FR and that the workability of the mortars with the addition of DSP increases substantially relative to the reference mortar (M10). But at a high rate of recycled fines, it is found that these fines have a negative effect on the workability (see Figure 5). The mortar without additions (M10) has good workability compared with mortars containing recycled fines in high rates. This profiler of prediction shows that with the design of experiments we obtain the maximum of information with the experiments minimum.

3.2. Modelling of mechanical strength

Mechanical characterization is obtained by using the measurements of compressive and flexural strength on 40 × 40 × 160 mm specimens according to standards NFP 15-403 [16]

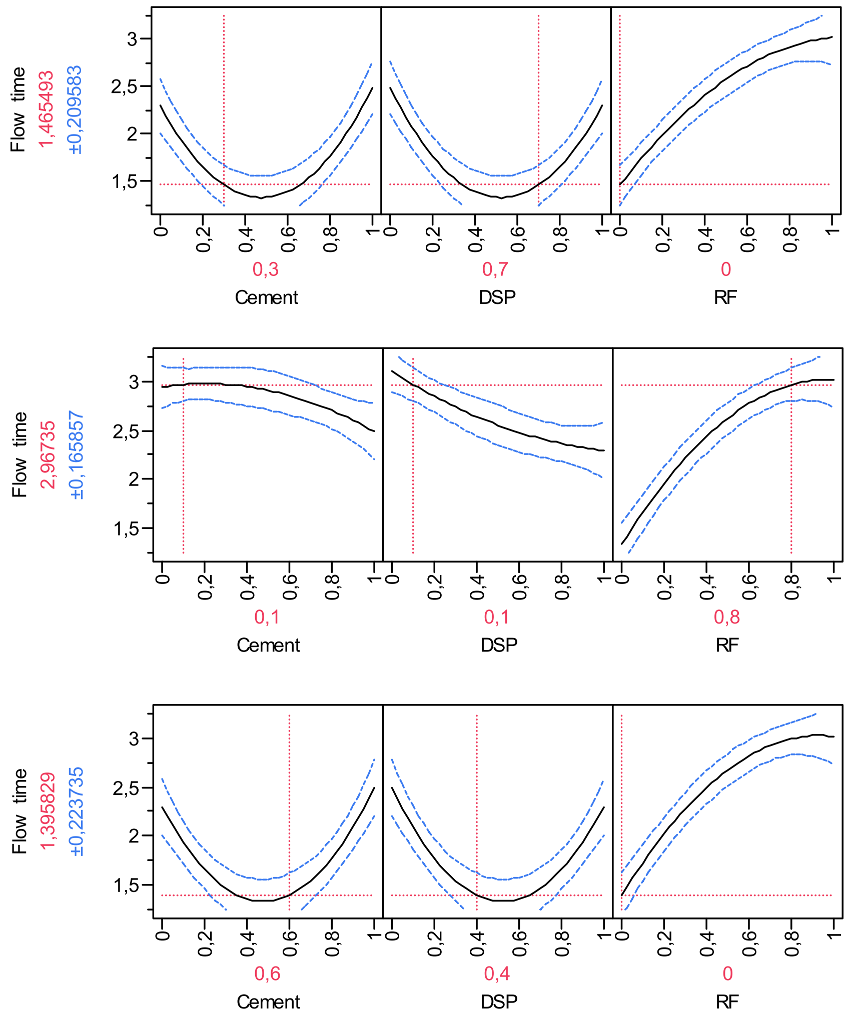


Figure 5. Profiler of flow time prediction as function of cement, DSP and RF proportions.

Table 9. Model parameters estimates of studied response (compressive strength at 28 days).

Summary of adjustment	
R^2	0.965893
R^2 adjusted	0.92326
Residual SD	1.772508
Average response	33.875
Comments (or weighted sums)	10

Estimates of coefficients

Term	Coeff.	SD	Ratio t	*p*-value
a1: (C)	37.27	1.66815	22.34	<0.0001*
a2: (DSP)	25.205714	1.66815	15.11	0.0001
a3: (RF)	33.55	1.66815	20.11	<0.0001 *
a 4: (C×DSP)	44.254286	7.384607	5.99	0.0039*
a5: (C×RF)	5.8371429	7.384607	0.79	0.4735
a6: (DSP×RF)	−16.49571	7.384607	−2.23	0.0892

Table 10. Model parameters estimates of studied response (flexural strength at 28 days).

Summary of adjustment	
R^2	0.959564
R^2 adjusted	0.909018
Residual SD	0.212535
Average response	8.298
Comments (or weighted sums)	10

Estimates of coefficients				
Term	Coeff.	SD	Ratio t	*p*-value
a1: (C)	7.5822857	0.200021	37.91	<0.0001*
a2: (DSP)	7.8808571	0.200021	39.40	<0.0001 *
a3: (RF)	7.2494286	0.200021	36.24	<0.0001 *
a 4: (C×DSP)	6.6921429	0.88546	7.56	0.0016*
a5: (C×RF)	4.5578571	0.88546	5.15	0.0068*
a6: (DSP×RF)	1.8385714	0.88546	2.08	0.1065

and NF EN 196-1 [17]. The flexural and compression strengths are reported as the average of three specimens and six specimens respectively. The model parameters estimates of studied responses (compressive and flexural strength at 28 days) are given in the Tables 9 and 10 respectively. According to these Tables, the mathematical models retained for the responses of compressive and flexural strength at 28 days are respectively written as follows:

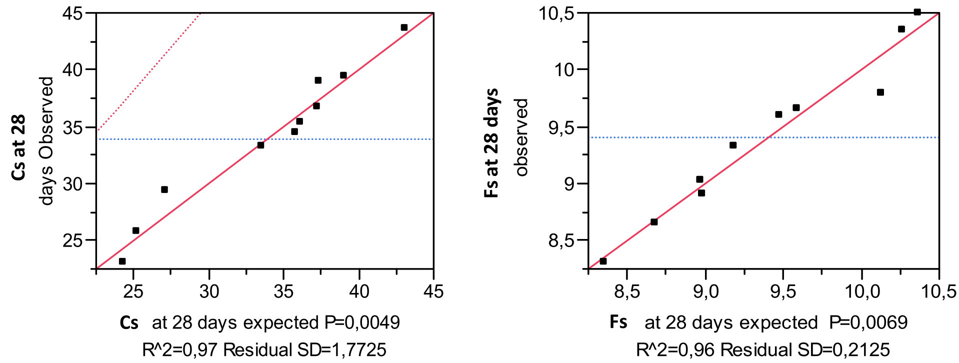
$$\mathbf{CS}(28\ days) = 37.27 \times \mathbf{C} + 25.2057 \times \mathbf{DSP} + 33.55 \times \mathbf{RF} + \mathbf{C} \times (\mathbf{DSP} \times 44.2543) + \mathbf{C} \times (\mathbf{RF} \times 5.8371) + \mathbf{DSP} \times (\mathbf{RF} \times -16.4957) \quad (8)$$

$$\mathbf{FS}(28\ days) = 7.5823 \times \mathbf{C} + 7.8809 \times \mathbf{DSP} + 7.2494 \times \mathbf{RF} + \mathbf{C} \times (\mathbf{DSP} \times 6.6921) + \mathbf{C} \times (\mathbf{RF} \times 4.5579) + \mathbf{DSP} \times (\mathbf{RF} \times 1.8386) \quad (9)$$

As indicated in the Tables 9 and 10, the models have relatively high correlation coefficients (R^2 = 0.97 for CS 28 days and R^2 = 0.96 for FS 28 days). This shows a good correlation between the responses obtained by the simulations and the values predicted by the models thus found. Negative sign coefficients indicate that an increase in the value of the associated

Table 11. Comparison between the expected and measured results of the mechanical strengths at 28 days (MPa).

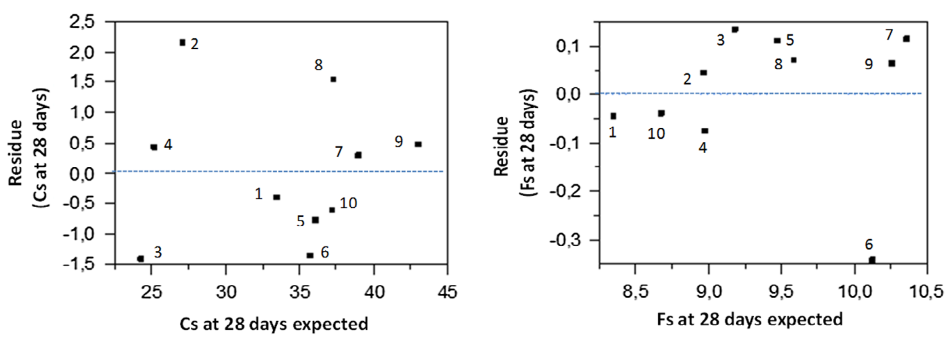
	Flexural strength		Compressive strength	
Mixture code	Measured	Expected	Measured	Expected
M1	8.30	8.34942857	33.11	33.5500000
M2	9.01	8.96847619	29.24	27.1028571
M3	9.31	9.17895238	22.88	24.3214286
M4	8.90	8.98085714	25.60	25.2057143
M5	9.58	9.47323810	35.27	36.0871429
M6	9.78	10.12514290	34.35	35.7414286
M7	10.48	10.36847620	39.32	39.0614286
M8	9.65	9.58419048	38.84	37.3271429
M9	10.33	10.26895240	43.52	43.0828571
M10	8.64	8.68228571	36.62	37.2700000



(a) Compressive strength (b) Flexural strength

Figure 6. Graph of observed values as a function of expected mechanical strength values.

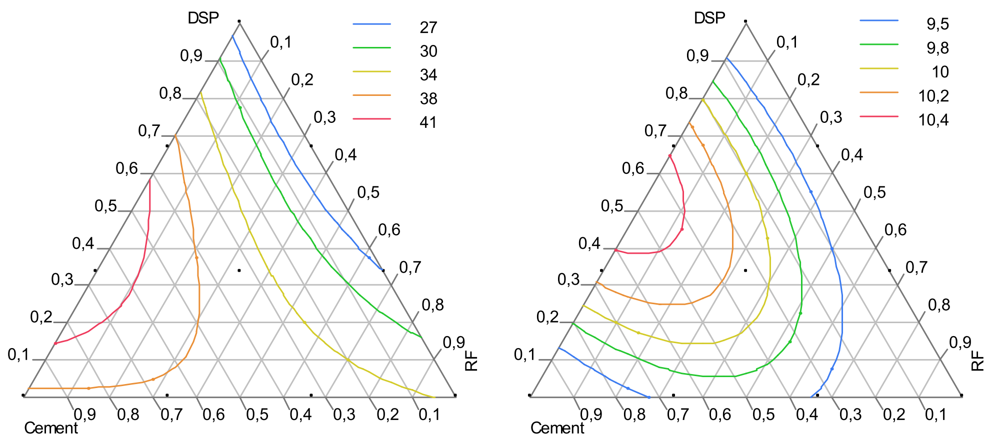
variable decreases the response and positive sign coefficients indicate that an increase in the value of the associated variable increases the response. For example, the increase in the DSP/RF couple decreases the measured mechanical strength. By cons, the increase in the C/DSP dosage increases the mechanical strength. We have noticed the interest of modelling the response studied by a polynomial which is then able to calculate all the responses of the field of study without being obliged to make all the experiments. The results obtained from the mechanical strength during the tests are compared in Table 11 with the results expected by the JMP7 software and are represented graphically in Figure 6. A classic technique is to verify if the model passes well by the measurements by calculating the gap between the measurements and the predictions of the model, or residue. If this residue is too large, one can then consider enriching or correcting the model, then possibly to update the experimental plan and to repeat other tests. The method can thus be implemented in an adaptive manner; that is to say by successively improving the model according to the insufficiencies encountered [18]. The graphic representation of the residues as a function of the expected responses (see Figure 7), allows us of to ensure that it does not remain information to extract from our results. In other words, residues graphs give an idea of the capacity of postulated models to represent the observed values. Indeed, it appears that the residues are randomly distributed (not a particular trend). So, we can say that the models



(a) Compressive strength (b) Flexural strength

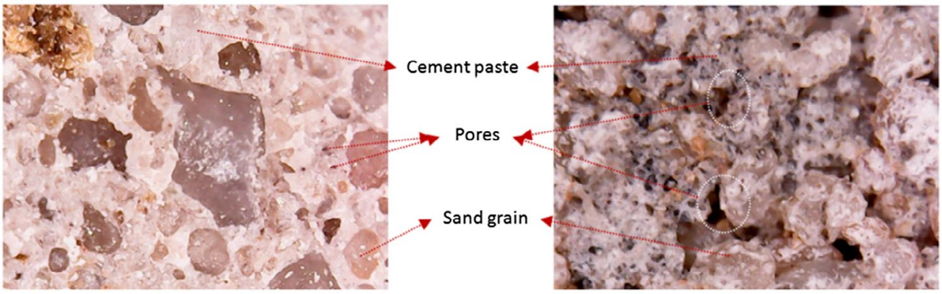
Figure 7. Diagrams of the residues.

resulting from the application of the experimental design method explain the experimental results well. The derived statistical models for the mechanical strength at 28 days reflect the relative significance of each parameter on the studied response. From these derived models, it can be noticed that the compressive strength at 28 days is first conditioned by coupled effect of cement and DSP, followed by the increasing the cement content, then the content of RF and finally the effect of DSP. By cons, the coupled effect of cement/RF and DSP/RF decrease the compressive strength due to the high percentage of cement substitution by the additions used. This decrease can be explained by the following observation: when the percentage of substitution of cement by additions increases, the amount of cement decreases, the resulting products fall, therefore, the quantity of $Ca(OH)_2$ with which the DSP and RF enters in reaction, decreases, which was resulting in a decrease in the quantity of C-S-H. Moreover, the amount of $Ca(OH)_2$ produced by the hydration of the cement is consumed by the reaction with the DSP (SiO_2), resulting in the addition of more strengthening C–S–H phase [6]. Indeed, the recycled fines (RF) have an physical effect, which may also contribute to filling of void. The DSP therefore participates by high percentage of silica SiO_2 compared to RF. The dosages of the three factors have optimum values (respectively around 66.66% of cement, 33.33% of DSP and 0% of RF in substituted volume of 112.5 kg of cement) for which the compressive strength reaches a maximum value. This finding reflects the chemical role of the DSP and confirms the pozzolanic activity of DSP at average and especially at long-term [2,4–7,19]. Indeed, the cement releases lime ($Ca(OH)_2$) during its hydration, the DSP fixing the lime to form new silicates (calcium silicate hydrate C-S-H II semi-crystallized of second generation) that lead to significant increases of mortar strength over time. Thus, the optimal strength is due to the physical role of the DSP which offers improved compactness to the mortars. In fact, the DSP can change the pores structure, reduce the number of large pores and increase the small pores. This change is a function of the fineness, the higher the filler particles, the more effective is their role [5,15,20]. Similarly, as for compressive strength, the flexural strength is also influenced by the substitution percentage of DSP and RF. One can observe that after 28 days, highest flexural strengths are that of mortars M7 (10.48 MPa) and M9 (10.33 MPa), with an optimum effect for the mortar M7 (respectively



(a) Compressive strength (b) Flexural strength

Figure 8. Iso-response curves of the mechanical strength of mortars as function of cement, DSP and RF proportions.



(a) M9-mortar (b) M10-mortar

Figure 9. Microscopic observation of the compactness of the studied mortars (magnification = 600×).

around 33.33% cement, 66.66% DSP and 0% RF). This is attributed to the partial pozzolanic reaction of the DSP [2,5–7,21,22], to form C–S–H II of second generation, which decrease the capillary porosity of the mortars causing an increase in flexural strength. Depending on the obtained results of the compressive and flexural tests at 28 days, we were able to build ternary graphs showing the effects of the three constituents of the studied responses (see Figure 8). Finally, the mortars studied have acceptable values of compression strength and flexion. In order to confirm the effect of the addition of dune sand powder (DSP) on the compactness of the studied mortar, M9 (mortar containing DSP) and M10 (mortar without DSP) were examined under a large scale with a device used for the microscopic observation of the material. The photographs thus obtained are shown in Figure 9. It is clear that the difference between M9-mortar and control mortar-M10 becomes more visible. These photographs clearly show that the M10 mortar (without additions) has a very porous structure in comparison with M9; it can also be seen that pores are developed especially around grains of sand. By examining the photograph obtained with M9 (with DSP), we quickly perceive that the structure of the latter appears much more compact, particularly in the transition zone around the grains of sand. Moreover, in M9-mortar, the sand grains appear well wrapped in the cement matrix, which increased the adhesion (paste-aggregates).

4. Conclusions

The main objective of this paper aimed to evaluate the physico-mechanical properties of mortars based on the addition of DSP and the RF using the mixture design modelling approach. The results also show that the adjusted models are good qualities and give important information about the effects of each of the parameters considered; of the graphs iso-responses, translating the mathematical models found into curves, could also validate the different noticed information. Based on the results of this study, the following conclusions could be drawn:

- The mixture design approach used in this experimental work was found to be an effective technique to investigate the effects of the three types of additions (cement, DSP and RF), in binary and ternary systems on the physico-mechanical properties of mortars.
- The interest of modelling the response studied by a polynomial which is then able to calculate all the responses of the field of study without being obliged to make all the experiments.

- The measurements obtained during the tests carried out allowed us to determine predictive models of workability, of compressive and flexural strength at 28 days.
- It can be seen that the presence of the DSP improves the workability of the mortars in the fresh state especially for the dosages 33.33 and 66.66% (i.e. d: 8.33 and 16.66% of total mass of the cement) relative to the reference mortar (M10). By cons, the recycled fines (RF) have a negative effect on the flow time.
- The introduction of DSP and RF in cement (by substitution) leads to a considerable improvement of mechanical strengths. The dosages of the three factors have optimum values (respectively around 66.66% of cement, 33.33% of DSP and 0% of RF in substituted volume of 112.5 kg of cement) for which the compressive strength reaches a maximum value. The compressive strength increases when the percentage of additions increases till an optimum (8.33% DSP and 8.33% RF), then decreases for larger percentages. One can observe that after 28 days, highest flexural strengths are that of mortars M7 and M9, with an optimum effect for the mortar M7 (respectively around 33.33% cement, 66.66% DSP and 0% RF).
- Finally it should be noted that not only the physico-mechanical properties of mortars are heartening, but the economic considerations, environmental and technical is also very interesting.

Disclosure statement

No potential conflict of interest was reported by the authors.

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