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Development of high performances concrete based on the addition of grinded dune sand and limestone rock using the mixture design modelling approach

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HIGHLIGHTS

- Dune sand and limestone rock were grinded in order to obtain economical mineral additions.
- SF and LF additions were added by substitution to the cement in order to formulate HPC.
- A mixture design modelling approach was used to highlight the effect of each addition.
- Statistical models predicting fresh and hardened HPC properties were established as function of C, SF and LF.
- Ternary contour plots were used to provide flexibility in optimizing C, SF and LF proportions.

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ABSTRACT

This paper presents the results of an experimental program in which the mixture design modelling approach was used in order to optimize the composition of a high performance concrete (HPC) formulated from local materials of the area of Laghouat (Algeria). The valorised materials are mineral additions: siliceous and limestone additions, obtained by fine grinding of dune sand and sieving aggregate crushing waste respectively. Both additions are added by substitution to the cement content. In order to model the influence of cement content and the dosages of these additions on the properties of high performance concrete, an experimental plans method with three factors was used. Mathematical models that explain at best test results which were identified and developed in this work. The modelling was performed thanks to statistical analysis software JMP7 of Statistical American Systems SAS-Institute. The obtained results showed that the introduction of siliceous fillers (SF) and limestone fillers (LF) in cement (by substitution) leads to a significant improvement in mechanical strength in the medium and long term which allows us to formulate a high performance concrete. In addition, the workability has been also improved with this substitution. Moreover, it was also shown that the use of the derived models based on the experimental design approach is very interesting and helps us to understand the interactions between the different parameters of the studied mixture (cement content, SF-content and LF-content). Finally it should be noted that not only the physic-mechanical properties are encouraging, but the economic aspect is also very interesting.

1. Introduction

High performance concrete (HPC) is a specialized series of concretes designed to provide several benefits in the construction of concrete structures such as the high mechanical strength and the good durability. The American Concrete Institute (ACI) defined HPC as “concrete which meets special performance and uniformity requirements that cannot always be achieved routinely by using only conventional materials and normal mixing, placing and cure” [1]. Indeed, HPC presents characteristic strengths at 28 days greater than 50 MPa and W/C ratio lower than 0.4 [2–4]. Its aggregates constitute a conventional granular skeleton embedded in a matrix of increased compactness thanks to the use of superplasticizer (water-reducing) and ultrafine crystalline or amorphous products which play both roles, as granular and pozzolanic complement

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[5]. In addition to Siliceous fume previously recognized as the best in this role, other ultrafine (slag, metakaolin, fly ash, ...) can be used [6]. Currently, the application of HPC in buildings becomes increasingly large due to its interesting properties regarding the compressive strength, tensile strength, ease of execution and implementation. However, the economical aspect is not completely absent [7]. Indeed, the current trend in the world is to find materials of different origins and compositions that can meet well-defined performance and minimizing cost [8]. It is in this aspect that we think about the use of the dune sand. The latter is a material of high availability in many countries around the world. Algeria is one of those countries where a large part of its territory is covered with this material. In fact, the use of dune sand in civil engineering has great economic and environmental interest. This material has been the subject of several research topics in recent decades [8,9]. As a mineral addition, it has been the subject of only some research topics which showed that the dune sand, in the form of mineral fines, is able to develop a certain pozzolanic reaction in cementitious environment [10,11].

For this purpose, it is advisable to add local raw materials that can achieve the same performance as those presented by Silica fume. Therefore, we proceeded to the use of grinded dune sand and limestone fines coming from crushing waste (abundant materials, and therefore relatively inexpensive) as additives in the context of minimizing the cost of HPC. Moreover, and to carry out the composition of the mixture studied, we used a new technique called " 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 [12]. Statistical modelling approaches are commonly used to identify the relative significance of primary mixture parameters and their coupled effects on relevant properties of concrete [13–16]. The aim of this work is to study the effect of the partial substitution of cement with Siliceous fillers (dune sand finely grinded (SF)) and limestone fillers (LF) (obtained from aggregates crushing waste) on the properties of HPC. This will select the most efficient optimal couples "SF/LF", both in terms of mechanical strength that sustainability point of view. For this, and as it has already been noted, 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

Besides the basic components (gravel, sand, cement, admixtures and water), HPC typically includes one or more additions [5]. In this study, dune sand (siliceous) was finely grinded and crushed waste (limestone) was sifted in order to incorporate the obtained fines as mineral additions in HPC. All used materials are characterized hereafter:

The used cement is a white blended Portland cement of type CPJ-CEM II/A 52.5 (initial limestone addition of about 12%) having high initial and final strengths. The cement factory conforms to the Algerian standard NA 442 [17] (which is mainly based on the European Standard EN 197-1). The chemical, mineralogical and physico-mechanical properties of this cement are given in Tables 1 and 2. The used additives are mineral additions of two different natures: siliceous fillers (SF) and limestone fillers (LF) (Fig. 1). SF are obtained by finely grinding dune sand. The latter is extracted from Algeria's northern region, near the city of Djelfa (Algeria) and featuring a maximum grain diameter of approximately 0.60 mm; the proportion of grains smaller than 0.08 mm is below 5%. The obtained fines are intended to be added by substitution to the cement. The sand is washed in order to remove any impurities, then dried and finally finely grinded until obtaining the desired grain size. The grinding was performed at dry state using a ball mill of large capacity which was pushed until obtaining a powder passing through a sieve of 80 μm. The specific density of the obtained powder (SF) is 2.6 g/cm^3. The mineralogical nature of "SF" is mainly siliceous which is shown in Fig. 2. LF are obtained by sifting (a sieve opening of 0.08 mm) crushing waste from a quarry located in the north region of Laghouat. The chemical analysis shows that these fillers are mainly composed of limestone (Fig. 3). Their specific density is of 2900 kg/m^3 and their specific surface is of 312 m^2/kg. The used sand is a river sand (RS) [18] which presents a continuous particle size distribution ranging from 0.08 to 5 mm with a fraction of grains smaller than 0.08 mm below 2%. Its particle size distribution is almost fully enveloped by the limit curves recommended for concrete (Fig. 4). In a schematic manner, RS grains present rounded shapes (Fig. 5). Table 3 lists the set of physical characteristics for this sand and EDX analysis of sands demonstrates its essentially siliceous nature (Fig. 6). The used gravel in this work is natural crushed gravel coming from the deposit located in the area of Laghouat. Two granular fractions were used: Gravel (3/8) and Gravel (8/15). Their particle size distributions are showed in Fig. 7 and their physical properties are listed in Table 3. Their chemical analysis is equally the same as that of limestone fillers (Fig. 3). The admixture used in this study is an Algerian superplasticiser, high water-reducer of third generation for ready concretes called MEDAFLOW 30. It should be noted that the total volume of mixing water is the volume of water to which must be added the equivalent quantity of water provided by the plasticizer [19].

Table 2
Physico-mechanical properties of the used cement.

Characteristics	White cement 52.5	
Specific density (kg/m^3)	3120	
Apparent density (kg/m^3)	1180	
Specific surface area (m^2/kg)	495	
Normal consistency (%)	25	
Initial set	1 h 45 mn	
Final set	2 h 60 mn	
Compressive strength (MPa)	2 days	30.69
	28 days	57.51

2.2. Mixture design approach

The mixture design approach consists of statistical methods that can be used to better organize experimental tests [20]. It can be applied in many disciplines and in all industries where several factors "xi" (in the case of concrete, the proportions of individual component materials) influence one or more performance characteristics, or responses "Y" (the fresh and hardened properties of the concrete). It is therefore very interesting to use this method when we have to study a function of type:

$$Y = f(x_i) \quad (1)$$

Indeed, when we use this technique, a maximum of information is obtained with a minimum of experiences. 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 [21]. 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 [22]. 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 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:

$$\sum_{i=1}^{i=n} x_i = 100\% \quad (2)$$

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

$$\sum_{i=1}^{i=n} x_i = 1 \quad (3)$$

Table 1
Chemical and mineralogical characteristics of the cement.

Sio$_2$	Al$_2$O$_3$	Fe$_2$O$_3$	CaO	MgO	SO$_3$	Na$_2$O	K$_2$O	LIO	C$_3$S	C$_2$S	C$_3$A	C$_4$AF
23.5	3.3	0.22	63.7	0.7	2.2	0.4	0.5	4.7	55.00	23.49	8.37	0.67