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A Study on Strength Properties of Concrete with Replacement of Low C_3A Cement by Fly Ash

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Abstract: The chemical composition of cement has a crucial impact on the performance of concrete. Different brands of Portland cement are used for various construction works without prior knowledge of their performance. For economic and environmental reasons, the valorization of fly ash in concrete production has been increasingly studied. The aim of this study is to determine the mechanical performance of the cement in which hydrated cement has been injected, and to assess the environmental benefit of using the waste as a partial replacement. The experimental study consists of replacing cement, with high tricalcium aluminate (C_3A) content, with cement with low C_3A content. The obtained result shows that it is very feasible to valorize this material and to manufacture eco-environmental cement which has rheological and mechanical characteristics almost similar to or better than that of ordinary cement, where a resistance of 30 MPa has been obtained, after a substitution rate of 50%. The valorization by using cement with low C_3A content makes it possible to strengthen the material at a young age and leads to obtain more economical and less polluting cement.

Key words: Concrete, fly ash, Expansion, Portland cement, mechanical properties, C_3A.

1. Introduction

The cement is one of the most traditional building materials in the world. Understanding the behavior of cement can lead to designing a high performance concrete in order to extend buildings lifespan and to improve the structural strength [1]. Faced with the growing needs for material resources and the environmental preservation, construction professionals become more aware of issues related to environmental preservation, the fact that urges them to study the end-of-life scenarios of concrete.

The economic and ecological constraints of recent years have made the recovery and the recycle of waste a necessity [2, 3].

The cement hardens when it comes into contact with water, by a way of a complex series of chemical reactions [1, 4]. This led to the use of cemented materials such as fly ash, silica fume, metakaolin, etc., which contribute to improving its performance [5, 6].

The use of fly ash and tricalcium aluminate (C_3A) by partially replacing the cement in the concrete, results in cement content reduction in concretes then in carbon dioxide (CO_2) emissions reduction [7, 8]. Also, the use of C_3A and fly ash has a positive impact on the conservation of existing resources and on the improvement of strength and durability of concrete [9, 10].

An experimental campaign was dedicated to the study, of the substitution of cement by Moroccan class F (fly ash) and its influence on the physico-chemical and mechanical properties of the substituted mortar, where the material strength remains acceptable up to 25% of substitution, but beyond this percentage, the substitution becomes detrimental to the mechanical properties of the material [11].

The experiments undertaken during this work have focused on the improvement of resistance at a young age and the exploration of various possibilities in order to increase the resistance under a rate of

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substitution beyond 25% [12].

A first study, has been devoted to increasing the specific surface of fly ash [13], by reducing the diameter of fly ash to 100 μm, in order to have more possibility of reactivity grains to form C-S-H bonds instead of C-H bonds [14]. The increasing of the reactivity makes it possible to create new links, which leads to decreasing the resistance at a young age [15].

Other studies have demonstrated that the grinding of fly ash up to 100 μm increases the resistance at a young age, which comes close to that of the unsubstituted material [13, 16].

However, the grinding has not allowed obtaining the acceptable mechanical properties with a substitution percentage of 50%. Because the bond created by grinding does not achieve the necessary rigidity of the solid phase, which makes it difficult to withstand the stresses developed by expansion [17, 18], this constraint has led us to develop other methods that directly address the origin of the material's expansion.

2. Materials and Methodology

In this study, a Portland cement (CPJ 45) is used, where the Clinker content presents 65% beside other additives such as limestone, fly ash, and/or pozzolans. Among the key features guaranteed by the standard, a minimum compressive strength of 32.5 MPa at 28th day is required, the CPJ 45 is used.

The CPJ 45 develops properties which allow this cement to be used in common reinforced concretes, which are intended for areas with a large mass, where the specific surface area of the CPJ 45 cement is between 3.2 m^2/g and 3.7 m^2/g. The results of this composition analysis are shown in Table 1.

The fly ash used in this study is produced in the Jorf Lasfar (Thermal Power Plant Morocco), after the burning of coal which comes from South Africa (Fig. 1). The chemical composition of the fly ash (Class F: silico-aluminous) has been determined by the X-ray Fluorescence technique. The size of the fly ash is 500 μm and its specific surface area is 2.8 m^2/g. Table 2 shows the results of this composition.

The mortars are produced with clean siliceous sand, where the sand presents 75% and the chloride content presents less than 0.2%.

To demonstrate the effect of alumina on our mortars of which 50% is substituted with fly ash, a cement containing 2% of C_3A, called also underwater cement, with more than 95% of clinker, has been used instead of CPJ 45 (Table 3).

This cement is mainly intended for concrete works, which is designed for water with high sulphate contents and for moderate to high aggressive environments. It can be used to reinforce concrete structures, unreinforced, prestressed by pre-tension or post-tension, where it is not subjected to heat treatment. It is particularly suitable for civil engineering works, wastewater treatment plants, foundation work, underground work, where it is not suitable for work requiring high short-term strength.

The demolding of mortars, which are prepared with an underwater cement, where the fly ash presents 50% (100 μm), came 24 hours after preparation has been completely finished, then the soaking is done in a tank of distilled water until the rupture according to the following times: 3rd, 7th, 14th and 28th days. The test of compression strength has been done according to the standard EN 196-1 (Fig. 2).

The density is measured after the demolding.

Table 1 Chemical composition of cement (%).

Compositions	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	P_2O_5	TiO_2
%	18.14	3.77	3.02	67.58	1.4	4.26	0.29	1.18	0	0.34

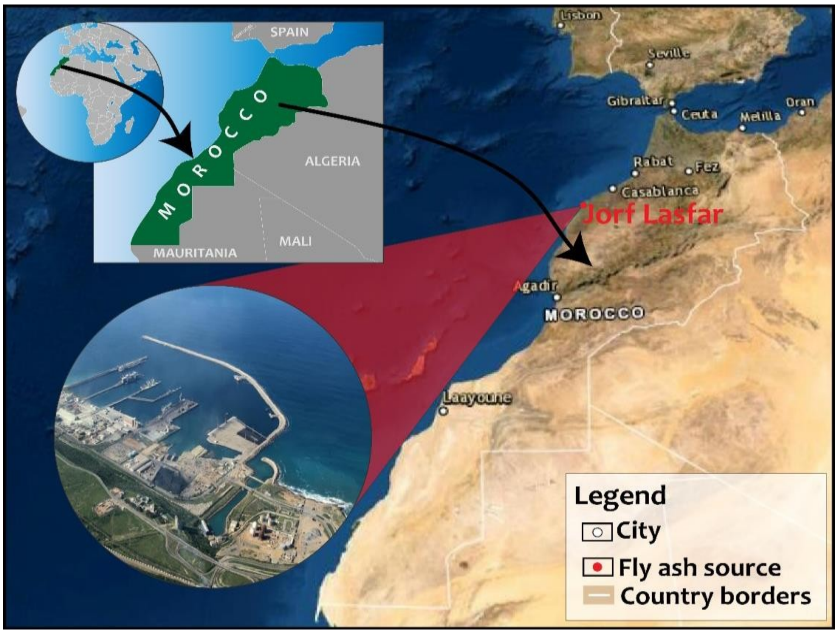

Fig. 1 Fly ash sources location.

Table 2 Chemical composition of fly ash (%).

Compositions	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	P_2O_5	TiO_2
%	50.05	32.13	5.07	5.06	1.08	0.82	0.69	2.13	1.16	1.82

Table 3 Chemical composition of low C_3A cement (%).

Compositions	S^{2-}	Al_2O_3	Cl^-	C_3A	MgO	SO_3
%	0.2	8	0.1	2	3	2.5

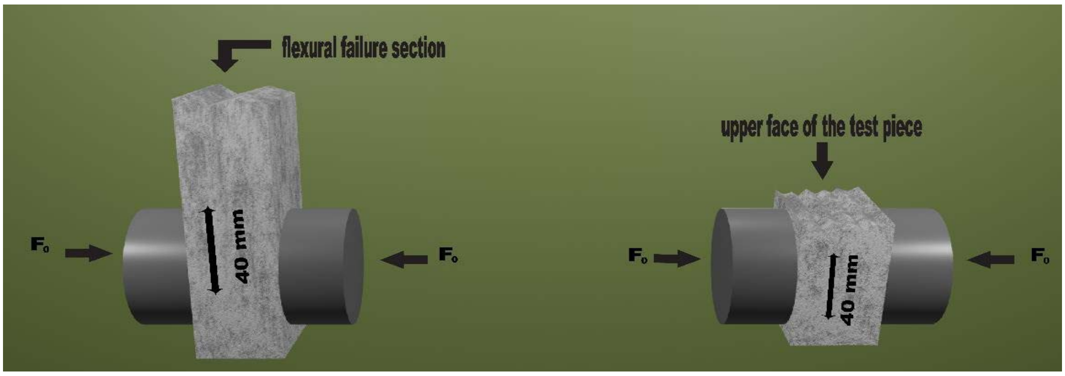

Fig. 2 Measurement of compressive strength on 4 × 4 × 16 cm^3 test tube.

3. Results

The evolution of the compressive yield stress (Fig. 3) shows that the substituted material produced with underwater cement has better mechanical properties, with higher values between the 3rd day and 14th day. On the other hand, the value of the breaking strength of the two materials comes close in the long term. The differences in the compressive yield stress are 21%, 35% and 28% at the 3rd day, 7th day and 14th day respectively.

It should be noted that the breaking strength reached at the 28th day exceeds 25 MPa for the material substituted with underwater cement. This resistance is often sought during the preparation of an ordinary concrete.

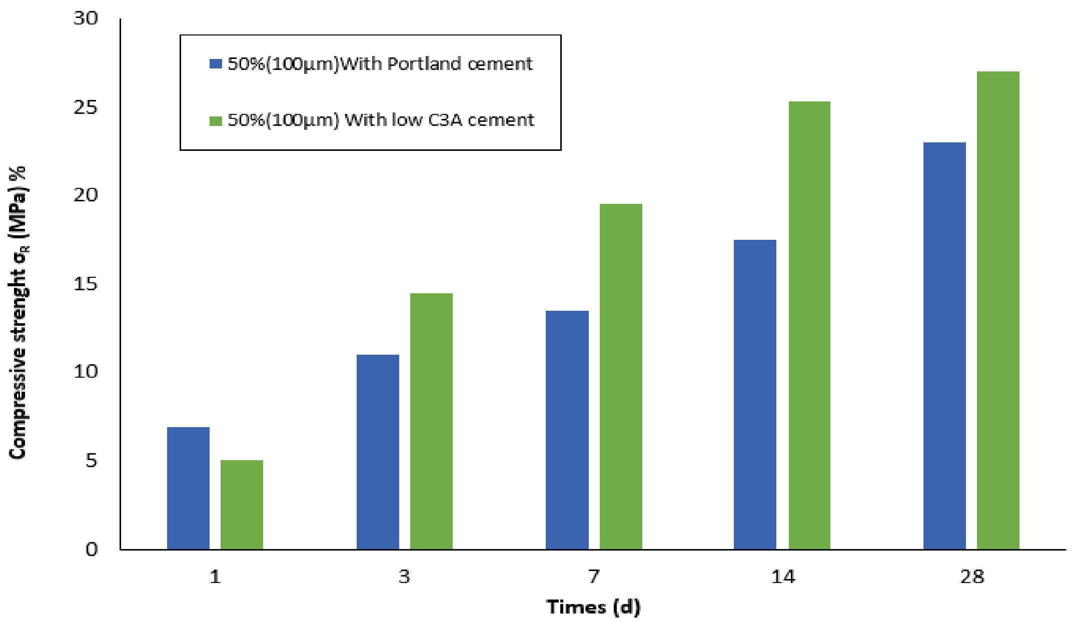

Fig. 3 Evolution of the compressive strength as a function of time with *E*/*L* = 0.4.

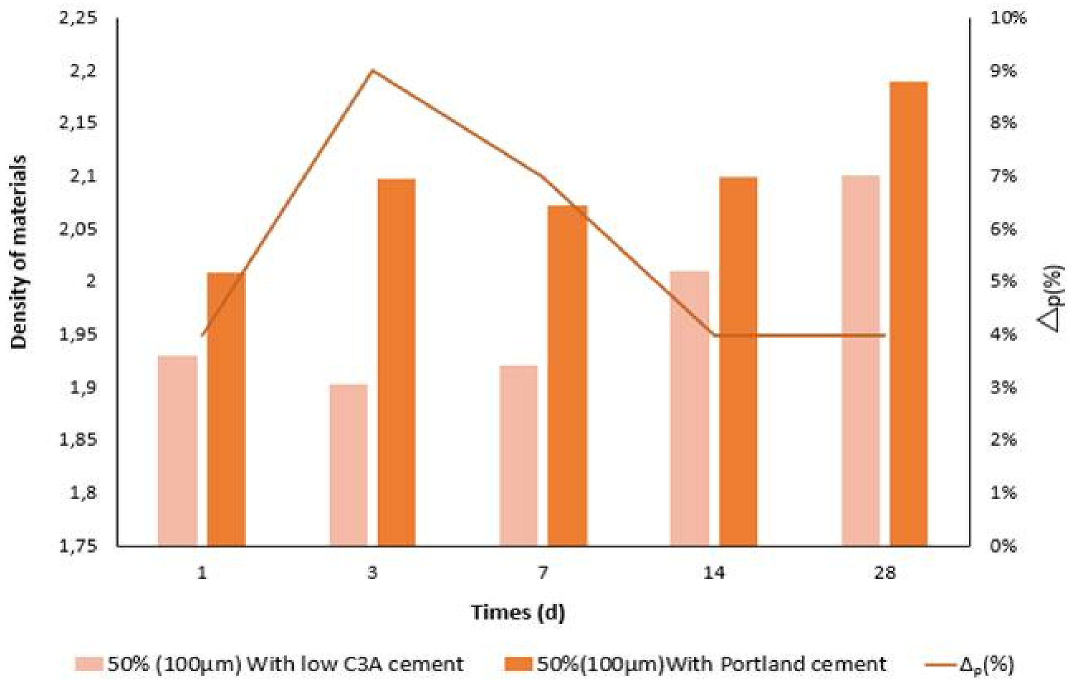

Fig. 4 The change in the density of the substituted material as a function of time with *E*/*L* = 0.4.

Fig. 4 shows the change in the density of the substituted material produced with cement with a low C_3A content (underwater cement) according to the different ages. The figure also shows the densities of the material substituted with CPJ 45.

The obtained results show that the density of the underwater cement is lower than that of CPJ 45 cement. The result is justified with the type of the used cement which delays the setting of materials and then the formation of a loose network [12]. This is confirmed by the analysis of the elastic modulus of the same material.

Fig. 5 shows that the elastic modulus of the mortar formed with underwater cement is low, especially at

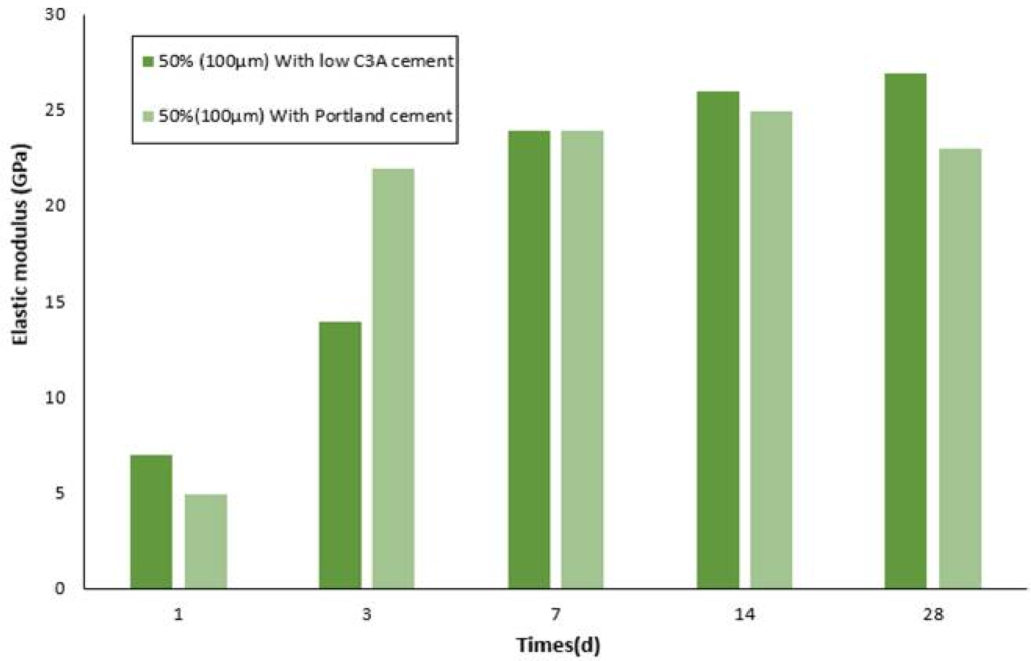

Fig. 5 Evolution of the elastic modulus as a function of time with *E*/*L* = 0.4.

the 3rd day with a value of 15 GPa, while a value of 22 GPa has been registered for the substituted material formed with CPJ 45.

4. Discussion

The used cement in the experimental study is characterized by a low C_3A content (2%) in order to obtain comparative values with the other cement which has a higher content in C_3A (8%).

The C_3A's role is not limited to that of a simple source of alumina [19]; The C_3A in this specific case plays also a role of catalyst, where the swelling is the only factor influencing the expansion of a substituted mortar with a high content of fly ash, even if it contains a high content of alumina.

The aluminate in Portland cement comes in two crystalline forms: the first is the most reactive C_3A and dissolves in the first minutes of hydration, where the second is the C_4AF, which is characterized with lower solubilization kinetics [20]. Because of that the role of the mineralogical form in the swelling has been studied where the substitution is made with fly ash (32% of Al_2O_3) (Table 2).

In order to highlight the influence of the amount of alumina with the reactivity of fly ash, which is a factor that influences the formation of ettringite [15], we monitored the compressive strength as a function of time.

Fig. 4 indicates that the mechanical results are increased by 20% to 35% at the 3rd and 7th days respectively, for a mortar with low C_3A content replaced with 50% of fly ash (100 μm).

The use of fly ash can be effective under certain conditions; its ability to control the swelling appears to be primarily a function of its CaO content [21].

The texture, the porosity and the permeability of the cement paste, caused by fines, are the most critical characteristics which cause the risk of swelling and also cause a drop in compressive strength in the early days. As a result, the texture of the material is improved at the level of the bonds even with a lime rate of 5%.

There is no correlation between the consumption of portlandite in the studied concrete and the reduction of the swelling [22]. But the reducing effect is attributed to its Al_2O_3 aluminate content—a determining parameter with regard to the possibility of ettringite formation [5].

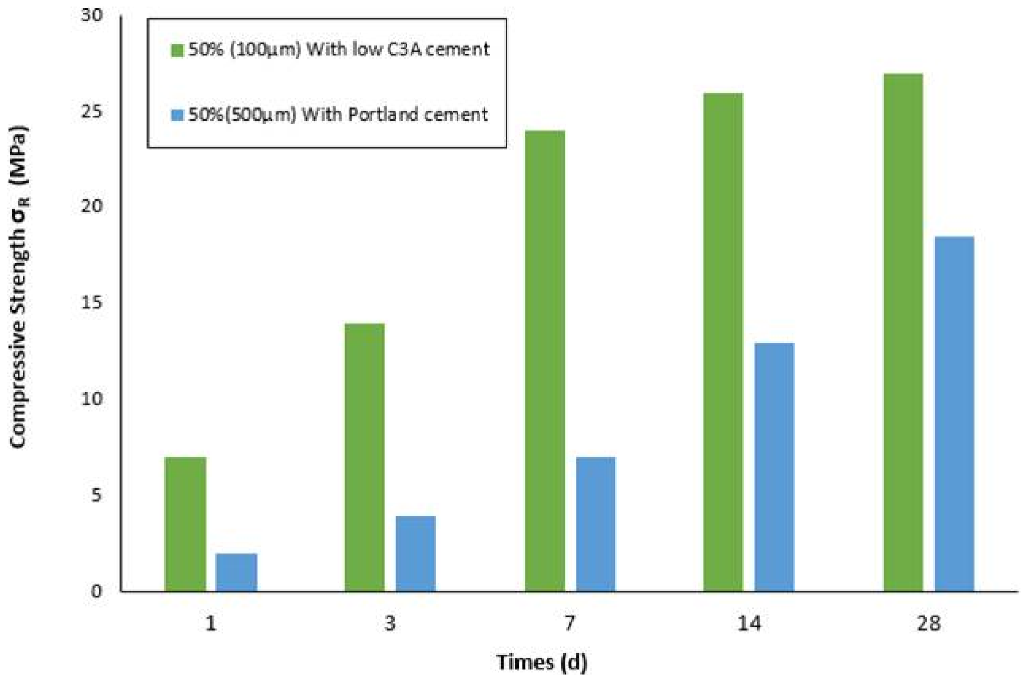

Fig. 6 Evolution of compressive strength as a function of age for mortars containing 50% fly ash.

The nature of the cement influences the texture of the cement paste in the first day of mixing. Indeed, the underwater cement is the main cause of the slow evolution of these grains at a young age [17]. More or less the compacted agglomerations of micro-grains, which assemble grains of larger size, have been demonstrated [23, 24].

The mineralogical composition of a cement—the C_3A aluminate and with less extend the C_4AF aluminoferrite, causes a significant variation in volume [19, 25]. As a result, the value of the modulus of elasticity measured on mortars (50% of fly ash) with CPJ 45 and underwater cement shows the same value from the 7th to 28th days. Therefore, the formation of new bonds, which lead to the strength less of the material, has been favored. And this is explained by the slowdown in the evolution of the modulus of elasticity at a young age (1 day to 3 days), due to the delayed pozzolanic activity and the lack of CH bonds in the case of mortar (50% fly ash) with a CPJ 45.

A comparison between the breaking strength of the material substituted with 50% of crushed fly ash up to 100 µm, which is verified using underwater cement, shows a considerable improvement of the breaking strength.

As for all the valuation studies that have been carried out [16], an increase by a factor of the order 3 at a young age (between the 3rd and 7th days), and by a factor of the order 2 at the 14th day has been detected (Fig. 6). It is important to study the breaking strength of all mortars at the 28th day [26, 27].

5. Conclusion

The mineral addition of fly ash causes swelling, therefore a detrimental effect on the mechanical properties at a young age. In addition to their chemical contribution, the fly ash often has the effect of densifying the structure of the cement paste. Therefore, it limits the possibilities of ion exchange, which favorites the precipitation of ettringite. In the light of this study, it is possible to conclude that the porous structure of the cement paste replaced by fly ash of class F (100 µm) is an important parameter regarding the behavior of the material.

The study also demonstrates that the use of cement with a low C_3A content (50% fly ash) makes it possible to obtain a substituted material with acceptable mechanical properties, especially at a young age. Therefore, the possibility of increasing the breaking strength at young age (7d) is by 65% and in long term (28 d) by 30%.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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