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Rheological and mechanical performance evaluation of high performance mortar based natural pozzolan

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ABSTRACT

This paper presents an experimental study on the rheological and mechanical properties of High Performance Mortar (HPM) based on natural pozzolan (NP). The specific surface BET of NP was 370 m²/kg used with different contents by weight of cement (5, 10, 15 and 20%). Two (w/b) water-binder ratios (0.35and 0.40) were used, the dosage of Superplasticizer (Sp) was kept constant (0.32 by weight of cement). The experimental results show that rheological properties of HPM increased with increasing NP content when w/b kept constant, but the increasing of (w/b) ratio led to decrease of both yield stress and plastic viscosity of mixtures.

The mechanical characteristics were improved with increasing NP content when w/b kept constant, but the increasing of (w/b) ratio led to decrease of both compressive strength. The optimal percentage substitution was 15% of NP, reducing CO2 emission by 20% for each cubic meter of mortar production.

1 Introduction

High mechanical strength and good durability of concrete provide several benefits in the construction of concrete structure [1], High Performance Concrete (HPC) is defined 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 by the American Concrete Institute(ACI) [2]. The higher strength of such concrete is caused by the low w/c ratio less than 0.40, the compressive strength of HPC is greater than 50MPa [3-5]. The compactness of mixtures is ensured by a conventional granular skeleton embedded in a matrix constituted by its aggregate, the use of superplasticizer (water-reducing) and ultrafine crystalline or amorphous products which play both roles, as granular and pozzolanic complement[6]. In the beginning, silica fume was employed as the best in this role, later, other ultra-fines such as natural pozzolan, slag and fly ash

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were used [7]. The interesting properties regarding the compressive strength, tensile strength and ease of execution and implementation, increase largely the application of HPC in buildings industry [1], However, the economical aspect is not completely absent [8]. Certainly, the current tendency in the world is to find materials of different origins and compositions that can meet well defined performance, minimizing cost [9], promoting ecological balance, conservation resources and reduce CO2emission [10].

Natural pozzolan can develop the properties of concrete, through the improvement of microstructure of concrete due to their particle size, may alter chemical composition and hydration reactions [11], The pozzolanic activities and chemical properties of the natural pozzolan differ depending on the region of the source [12]. As an amorphous or glassy silicate material that reacts with calcium hydroxide formed during the hydration of Portland cement in concrete [11]. Calcium hydroxide reacts with silica contained in natural pozzolan to form extra calcium silicate hydrates compound and diminish calcium hydroxide [13]. Many researchers studied the performance of concrete containing natural pozzolan [14-17]. The increase of C-S-H makes concrete stronger, denser, and durable during its service life [11].

The aim of this paper is the assessment of properties of high performance mortar (HPM) using natural pozzolan as a fractional replacement for cement substitute, with different w/b ratios. To achieve this, rheological parameters defined by the yield stress and plastic viscosity [18], and mechanical properties of high performance mortar (HPM) are measured to ensure that fundamental parameters needed in design are evaluated.

2 Experimental Procedure

2.1 Material and mix proportion

In this study, an Ordinary Portland Cement (C) type CEM I 52.5 with a specific surface Blaine of 359 m^2/kg was used for all mortar mixtures. One type of Natural pozzolan was employed, with a specific surface Blaine of 370 m^2/kg and 2.30 of density, Table 1 summarizes the chemical composition of cement and natural pozzolan.

Table 1 - Chemical analysis of cement and natural pozzolan.

Oxides (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	SO_3	Na_2O	Loss on ignition	Insoluble residue(IR)
Cement (C)	20.23	4.29	2.35	63.67	3.88	0.69	2.80	0.14	1.63	0.39
Natural pozzolan (NP)	37.84	14.74	14.10	5.34	3.03	0.73	0.25	0.75	-	-

The superplasticizer (Sp) used is Tempo12 by Sika, with 30.2±1.3% solid content based on acrylic copolymer. The Sp dosages are referred to the aqueous solutions and not to the solid fraction by weight of cement. The sand used in mortar mixes was natural sand (0/4) sand of 4 mm maximum aggregate size, with a density of 2.53 and fineness modulus of 2.64, the grain size curve is showed in Figure 1.

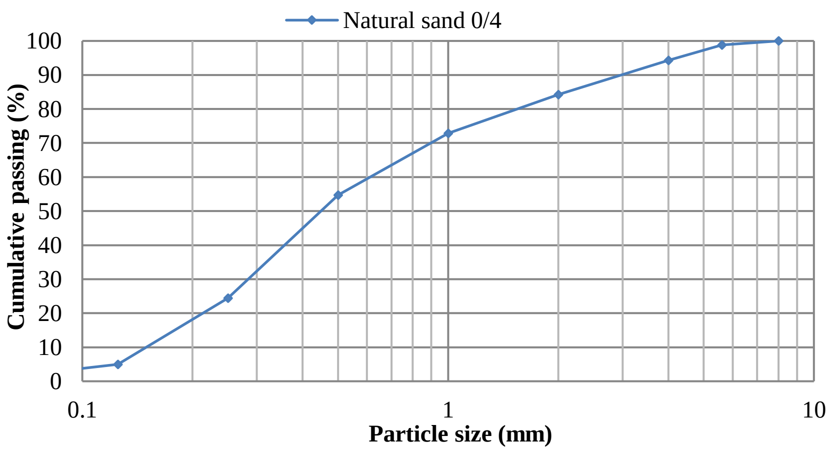

Fig. 1 –Grain size curve of natural sand 0/4

The particle size distributions of cement and natural pozzolan, were measured using a Malvern laser diffraction instrument (ASTM E2834-12) and are showed in Figure 2.

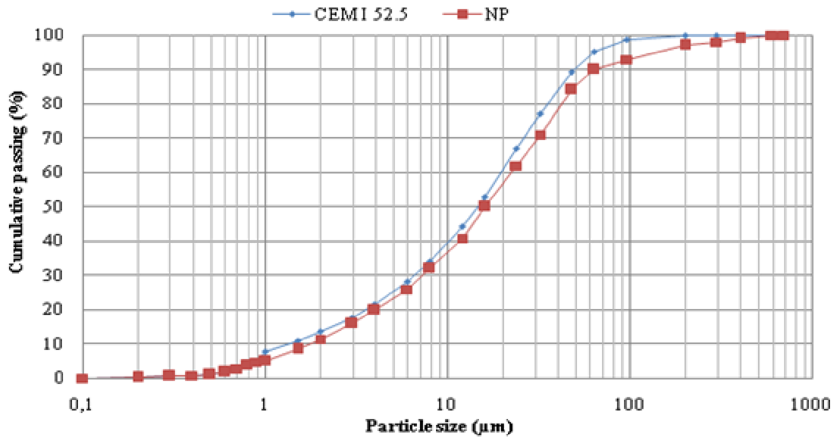

Fig. 2 – Particle size distribution of cement and NP

To well understand the effect of content of NP on the rheological and mechanical properties of HPM, mortar series were made by partially replacing NP with cement by weight (percentage varying from 0 to 20%, with the increment of 5%)and kept Sp/C ratio constant (SP/C= 0.32) for all mixes with two water-binder ratios (w/b =0.35 and 0.40). The compositions of the mortar are summarized in Table 2. Mixtures based w/b =0.40 were coded by M1-x%, however, mixtures based on w/b =0.35 were coded by M2-x%, where x% represented the substitution percentage of natural pozzolan.

Table 2 - Mortar composition with Sp = 0.32 %.

Mixture	w/b	W *(kg/m³)*	NP/C *(%)*	C *(kg/m3)*	NP *(kg/m³)*
M1-0%			0	450	0
M1-5%			5	427.5	22.5
M1-10%	0.40	180	10	405	45
M1-15%			15	382.5	67.5
M1-20%			20	360	90
M2-0%			0	450	0
M2-5%			5	427.5	22.5
M2-10%	0.35	157.5	10	405	45
M2-15%			15	382.5	67.5
M2-20%			20	360	90

2.2 Mortar preparation

The same mixer and mixing procedure were used for all mixtures to eliminate the effect of mixing procedure and equipment on the rheological properties. According to European Standard EN 196-1, a mixer at stage I (62.5 rpm) was used to prepare the fresh mortars. The dry mortar constituents were mixed for 1 min. Water with Sp was added progressively during the next 30 sec. After continuing the mixing for 1 minute it was stopped for 30 in order to scrape off the material that had adhered to the sides of the mixing bowl with a plastic spatula. After that, it was followed by a second mixing for 1 minute [19].

2.3 Test methods

In order to evaluate the rheological characteristics, two tests, specifically a mini-cone, and rheological test were done to characterize the rheological behaviour of the different mortars. The first test measured the slump flow and the spread flow;

the second test measured the flow time, and the rheological properties were measured in the last test. Testing details are given in the section below.

2.3.1 Mini-cone test

A cone with a half of values given in the norm NF EN 12350-2, with an upper diameter of 50 mm, a lower diameter of 100 mm and a height of 150 mm was used to evaluate the spread and the slump of mortar. After one minute, and lifting gently the cone, the appropriate spread is given by the average value of two individual and perpendicular diameters of the pad formed. However, in order to sweep a wide range of consistency, the slump was measured in parallel to the spread test [20].

2.3.2 Rheological test

The rheological test of mortar is used to illustrate the mortar flow considered as a fluid. The cement past, mortar and concrete flow behaviour can be described with sufficient accuracy by the Bingham model [21-24]:

$$\tau = \tau_0 + \mu \dot{\gamma} \quad (1)$$

where τ is the shear stress applied to the material, τ_0 is the yield stress, μ is the plastic viscosity and $\dot{\gamma}$ is the strain gradient (also called the shear strain rate). The Rheometer used was developed and validated by Soualhi et al. [25]. It is composed of three main parts: An agitator with electronic speed control for recording the torques, a container, and a steel vane. The agitator characteristics are rotational speed from 4 to 540 *rpm* (± 1 *rpm*) and maximum torque of 740 *Ncm* (± 0.1 *Ncm*). The vane dimensions are 10 *cm* in height and 5 *cm* in diameter. The container is a cylinder of 10 *cm* in diameter and 13 cm in height (Figure 3).

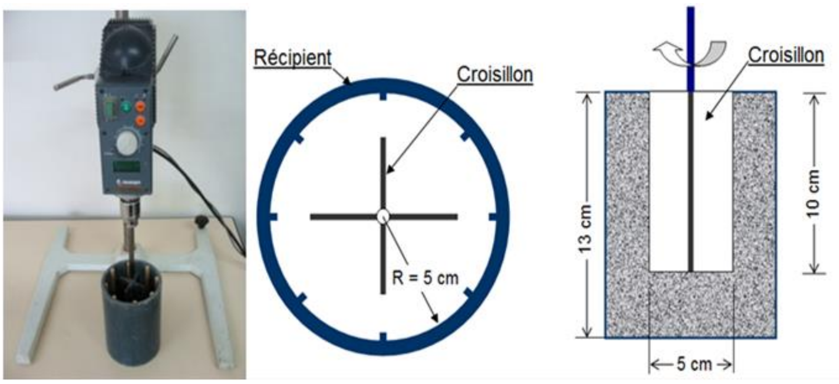

Fig. 3 – Rheometer and position of the vane in mortar

The principle is to rotate, at different speeds, a vane in a cylindrical sample of fresh mortar and measuring the torques exerted to maintain rotation. A rheological test is performed by imposing a decreasing rotational speed to the vane interrupted by a stabilization stage to perform the measurements (Figure 4). To develop the rheological parameters from measurements, a procedure was used to convert the vane torque and rotational velocity data into shear stress versus shear rate relationships.

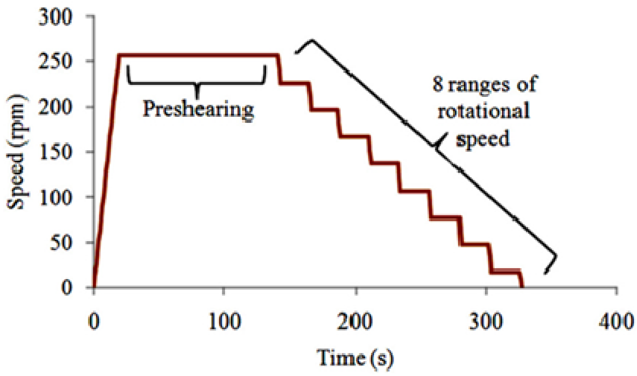

Fig. 4 – The profile of the imposed rotational speed P257

The used procedure considered the locally sheared material as a Bingham fluid and computed the characteristic shear rate from Couette analogy [19, 25-30].

2.3.3 Compressive strength

Prismatic (40 × 40 × 160 mm) specimens were used to evaluate the compressive strength of the mortars according to EN 12390-1, EN 12390-2. All the moulds were covered by plastic sheets and stored for 24 *h* in the laboratory prior to demoulding afterwards; they were cured into water at 20±2°C. The tests are conducted at different test ages of 7, 28, and 90 days. Also to show the strength gain with the time, all experiments were performed on three specimen replicates.

3 Results and discussion

To investigate the influence of natural pozzolan on the rheological properties of HPM, many types of mortar were prepared by varying the percentage of cement replaced, with an increment of 5%, by the studied additions from 0 to 20% by weight of the binder.

3.1 Mini-cone test results

Figure 5 illustrates the spread and the slump for mortars based on NP. The tests were done at different w/b ratios of (0.35 and 0.40) and a fixed *Sp* dosage of 0.32 by mass of cement. It is clearly observed that the slump and spread were slightly decreased with increasing content of *NP* for both of w/b ratios used. Generally, the addition of NP affects slightly the workability of mortar.

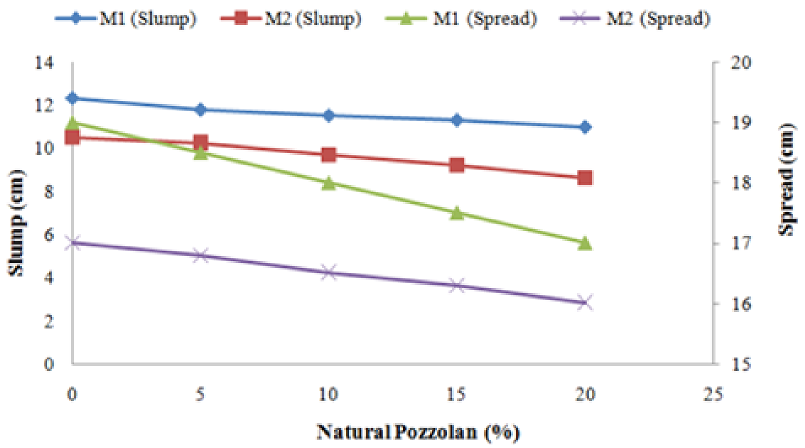

Fig. 5 – Influence of NP content on the flow properties of HPM

This is due to water demand and the difference recorded in specific surface area between NP and cement. According to Belaidi et al [31], the use of pozzolan by substitution to cement has no negative effects on the workability of SCC. The substitution of a material with another one of different specific surface area can change the wet surface area and the amount of water adsorbed. Some addition shaving a certain water solubility may change the electrolyte solution and thus the electrostatic forces. These results are in good agreement with those already published [32-34].

3.2 Rheological tests results

To determine the rheological parameters, the used procedure considered the sheared material as a Bingham fluid, according to Soualhi et al. [25].

The evolutions of the shears stress with the shear rates are given in Figures 6a and 6b. The results illustrate that the studied mortars behave as Bingham materials. The yield stress is obtained by extrapolation of the descending branch of the curves to intersect the shear stress axis, and the viscosity is the diagrams' slope [19].

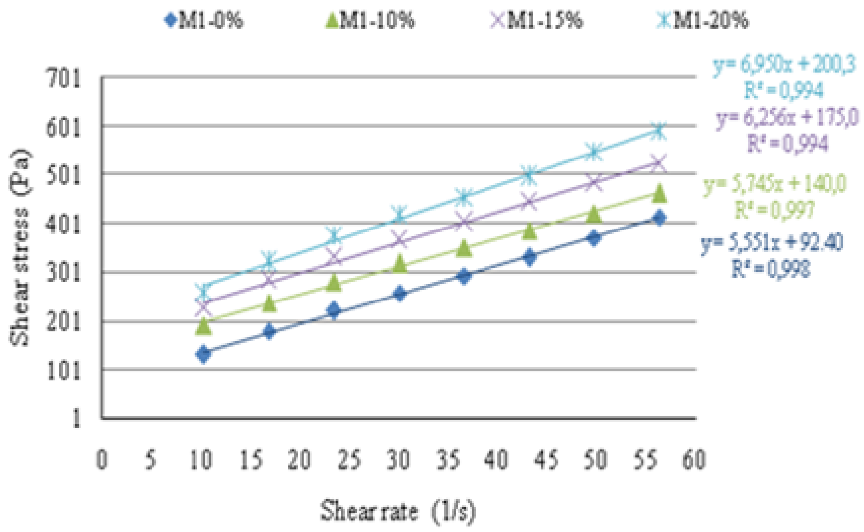

Fig. 6.a – Effect of NP content on the evolution of the shear stress with shear rate: (w/b=0.40

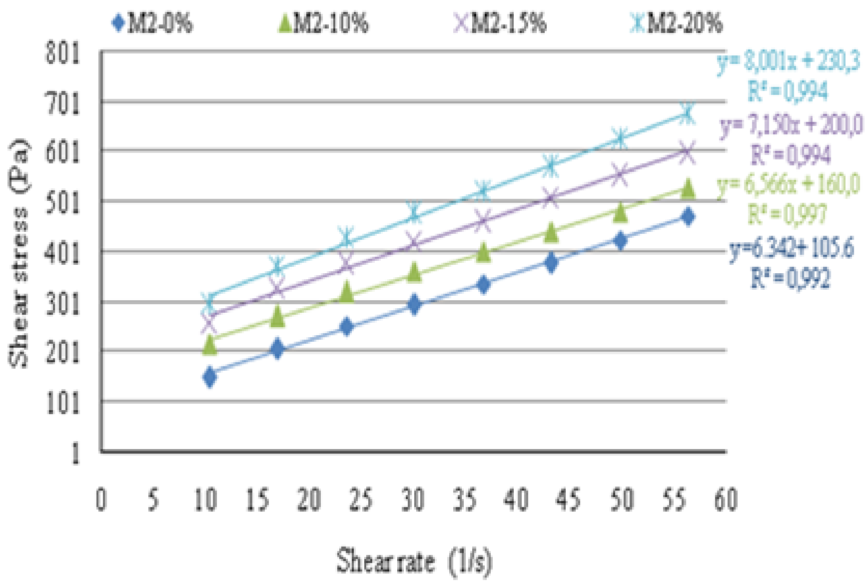

Fig. 6.b – Effect of NP content on the evolution of the shear stress with shear rate: (w/b=0.35)

The variation of rheological parameters as the yield stress and the plastic viscosity according to the replacement rate of natural pozzolan with different w/b ratios are shown in Figures 7a and 7b. The results show that:

- the yield stress value of cement mortar increases linearly with the increase of the substitution rate of natural pozzolan (NP).That can be explained by the fact that the diminution in the w/b ratio causes a diminution in the workability due to the lowering of the quantity of mixing water, and consequently an increase in the yield stress.This results confirm that of [35];
- the cement mortar viscosity increases non-linearly with the augmentation of the addition of NP.
- the W/C ratio influence the rheological parameters with natural pozzolan [24].

M Sahmaran et al. [36] found similar results for mortar based zeolite, the increase of zeolite amount, increases both of the yield stress and the plastic viscosity for a constant superplasticizer dosage. Natural pozzolan has comparable rheological behaviour as silica fume due to the increased interactions between fine particles [36].A partial substitution of cement by natural pozzolan in higher volume of paste, increases the volume paste caused by the lower density of NP, and increases the plasticity and cohesiveness, thus it makes mixtures less fluid [36].

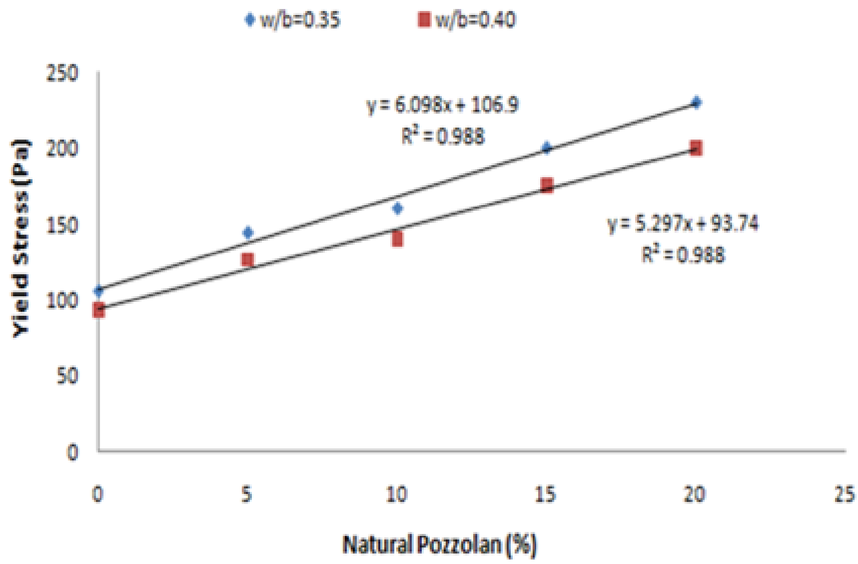

Fig.7.a – Influence of NP content on the yield stress with different mortars

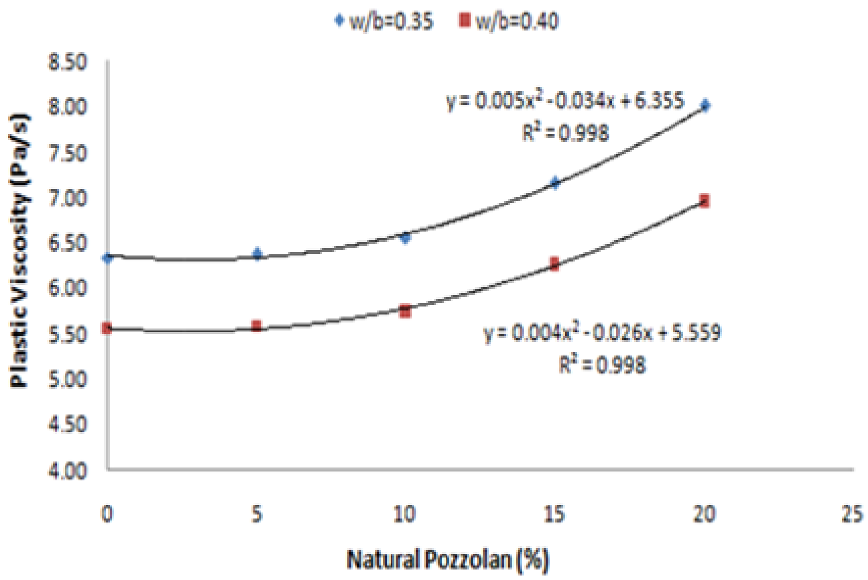

Fig. 7.b – Influence of NP content on the plastic viscosity with different mortars

3.3 Mechanical performance

According to EN 12390-1 and EN 12390-2, cubic ($40 \times 40 \times 160\, mm^3$) specimens were used to measure the compressive strength of mortar at age of 7, 28 and 90 days. All the moulds were covered by plastic sheets and stored for 24 h in the laboratory prior to demoulding afterwards; they were cured into water at 20 °C.

Relationships between pozzolan amount and compressive strength were performed for each type of mortar to obtain the pozzolan amount which provides the greatest strength.

Figures 8a and 8b presents the trend of pozzolan– strength curves, it was remarkably noticed that the compressive strength increases with the incensement of amount of NP until an optimum amount of 15% for each w/b ratio (0.35 or 0.40) by 17% and 25% at 28 and 90 days of curing age, after this percentage compressive strength decreases. Decreasing of the strength curve after a maximum point may be caused by the defect effect of un-hydrated pozzolan [37].

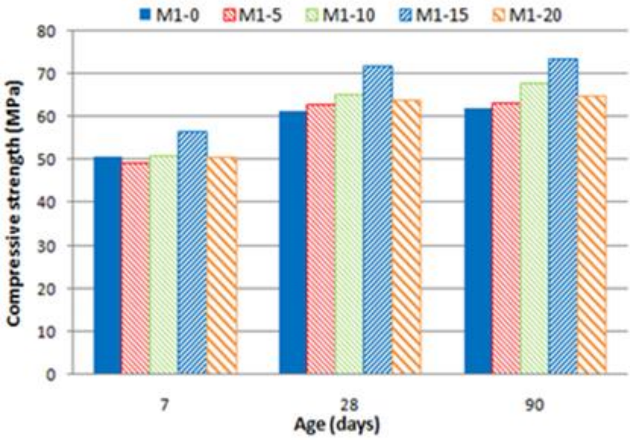

Fig. 8.a – Influence of NP content on the compressive strength: (w/b=0.40)

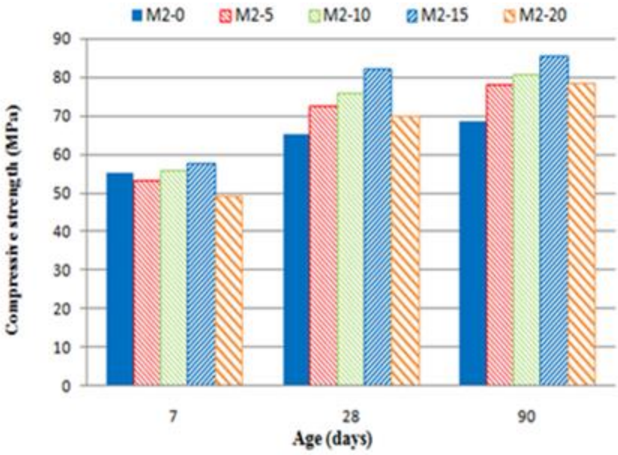

Fig. 8.b – Influence of NP content on the compressive strength: (w/b=0.35)

The ultimate strength is considerably modified in the presence of natural pozzolan in the composition of binder. As shown Ezziane et al. [38] that the variation of the ultimate strength obtained shows parabolic curves giving an optimal replacement rate correspondent to the maximum strength. The estimated pozzolan content optimum was 15% for 20°C of curing temperature, when, Pekmezci and Akyuz [37] found that the optimum pozzolan/ cement ratio to obtain maximum strength is about 28%. Shannag and Yeginobali [39] judged that the mix with 25% natural pozzolan was the optimum, the different origins and compositions of natural pozzolan can meet well defined the mechanical performance of concretes [9].

At seven days, the compressive strength of the specimens containing natural pozzolan is lower by 4% than that of the plain mortar, natural pozzolan may not participate in hydration which could be due to their low pozzolanic reaction between silica in pozzolana and the calcium hydroxide liberated during the hydration of mortar. Progressively, at the age of 28 days, the pozzolanic reaction led to a significant increase of the compressive strengths of mortars. Especially after 90 days[40],the compressive strength of the specimens containing natural pozzolan is relatively enhanced, which indicates that natural pozzolan has compensated its lag in the production of C-S-H gel [41].

4 Conclusion

This study focused on a laboratory evaluation of the mechanical performance of HPM mixtures using natural pozzolan. A comparison research was carried out for two different w/b ratios and many natural pozzolan amounts. Based on the laboratory experiments and analyses, the following conclusions can be summarized as follows:

- The increase of the percentage of Natural Pozzolan decreases the slump and spread of mortar for both $w/b = 0.35$ and 0.40.

- The increase of the w/b ratio increases the slump and spread by about 22% and 5% respectively.
- The increase of the percentage of Natural Pozzolan increases rheological properties (of yield stress and viscosity) for both $w/b = 0.35$ and 0.40.
- The increase of the w/b ratio decreases the yield stress and viscosity of HPM by 13%.
- At early ages, the compressive strength of the specimens containing natural pozzolan is lower by 8% than that of the plain mortar, progressively, at the age of 28 days, the compressive strength of the specimens containing natural pozzolan is relatively enhanced, and furthermore it is significantly increased at the age of 90 days.
- For both w/b ratios used ($w/b = 0.35$ and 0.40), compressive strength increases by 25% for an optimum of 15% of natural pozzolan substitution, the more increasing w/b the more decreasing the compressive strength (about 4%) at 90days.

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