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Physical Mechanical Properties and Durability of Mortars Containing Tuff from Burkina Faso as Partial Substitution of CEM I

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Abstract This paper presents the feasibility of using locally available limestone Tuff in Burkina Faso as a partial replacement for CEM I artificial Portland cement. To this end, standard tests were carried out in the laboratory on mortars containing variable proportions of Tuff in partial substitution of CEM I cement. These include heat of hydration, setting time, total shrinkage, compressive strength, capillary absorption and resistance to acid attack. The experimental results obtained show that Tuff can be used as a natural pozzolan. It is also noted that the incorporation of Tuff into cement has virtually no influence on the transfer properties of mortars. However, at a rate above 15% partial substitution of CEM I, the mechanical strength of mortars is considerably reduced. This is probably linked to the finesse of the Tuff used. A finer shredding improved the mechanical activity index. However, we note a better resistance to acid attack (sulphuric acid that can come from acid rain) of mortars containing Tuff compared to mortar based on artificial Portland cement. All these results have shown that the Tuff used in this work can be a solution for reducing CO_2 emissions in cement production and also in reducing the price of cement in Burkina Faso.

Keywords: *Tuff, Natural pozzolana, Eco-cement, Mortar, Durability*

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1. Introduction

Throughout the world, people are increasingly concerned about their environment and its preservation to ensure quality of life. As well as, research is increasingly oriented towards solutions that could guarantee sustainable buildings ensuring a quality of life for their operators with a mastery of their impact on the environment and their energy performance. Africa, which remains the second most densely populated continent after Asia, with an annual urbanization rate of around 4% and according to UN-Habitat, 80% of the buildings that will be inhabited in 2050 are not yet built and Africa needs nearly 4 million dwellings per year, of which more than 60% to house city dwellers [1]. In Burkina Faso, for example, major construction projects such as interchanges, sustainable cities, administrative complexes, social housing, etc. are opening up. These constructions generate a significant consumption of cement, which is well known for its high cost and greenhouse gas emissions during its manufacture. Indeed, one tonne of cement produced is equivalent to one tonne of carbon dioxide emitted into the atmosphere [1]. Cement industries are at the forefront of global atmospheric polluters [2].

It is therefore essential and topical to find innovative, local and ecological materials that can partially replace clinker in the cement manufacturing process. The literature shows that the use of pozzolans contributes to improving the mechanical strength of concrete through the manufacture of second generation C-S-H by consuming portlandite, reducing porosity and reducing alkali-silica reactions [3,4]. It is with this in mind that we thought of the Tuff, which is found in large quantities in Burkina Faso. The Tuff has already been the subject of some research which shows that it presents a pozzolanic reactivity [5,6].

In Burkina Faso, clay materials are already the subject of scientific work for their valorization [7,8,9] in construction. However, there is little literature on the use of Tuff in the cement industry, except in Algeria, where more than 50% of the cement plants that use calcareous Tuffs as pozzolans in the manufacture of cement are found [10]. However, several works have been devoted to the stabilization of calcareous Tuffs with cement in road construction in certain countries such as United States (USA), Argentina, Tunisia [7,11,12,13,14]. It should also be noted that Tuffs are used as a source of calcium carbonate for various industrial applications [15]. In one study, Balata et al. [16] showed the possibility of using Tuffs blocks as masonry elements.

The objective of this research work is to contribute to the valorization of Tuff, a natural material available in Burkina Faso, in the cement industry as a substitute for clinker. Specifically, it is a question of determining the influence of the partial substitution of the artificial Portland cement CEM I by Tuff on the physico-mechanical and durability properties of a mortar.

2. Experimental Materials and Methods

2.1. Materials

2.1.1. Cement

CEM I 42.5 N cement (produced by CIMTOGO) is used for the manufacture of mortars. Its chemical composition and physical properties are presented in Table 1. It has a specific density of 3.1 t/m^3 and a Blaine fineness of 3565 cm^2/g. Laser particle size analysis indicates that it has a maximum diameter of 50 µm (Figure 2) and a median diameter D50 of 10.5 µm. The setting times of this cement determined in accordance with EN 196-3 [17] is approximately 138 minutes.

Table 1. Chemical and Mineralogical Composition, Physical Charateristics of CEM I and Tuff

	CEM I	Tuff
Oxides	Chemical Composition (%)	
SiO_2	18.6	60.4
CaO	59.6	2.5
Al_2O_3	4.73	16.61
Fe_2O_3	3.11	5.54
K_2O	0.26	1.21
Na_2O	0.10	1.87
MgO	2.57	1.17
MnO	0.085	0.04
TiO_2	0.24	0.52
Cl	0.03	-
SO_3	2.62	-
SrO	0.024	-
P_2O_5	0.47	0.10
Loss of ignition	7.5	7.18
	Mineralogical Composition (%)	
Montmorillonite	-	7.21
Kaolinite	-	7.99
Muscovite	-	22.62
Quartz	-	32.91
Goethite	-	3.66
Albite	-	25.61
C_3S	60.2	-
C_2S	14.9	-
C_3A	7.9	-
C_4AF	10.1	-
	Physical Characteristics	
D10 (µm)	1.1	2.3
D50 (µm)	10.5	8.9
D90 (µm)	34.6	60.3
Specific density (t/m^3)	3.10	2.65
Apparent density (t/m^3)	1.06	0.86
Fineness modulus	-	1.27
Blue value	-	0.9

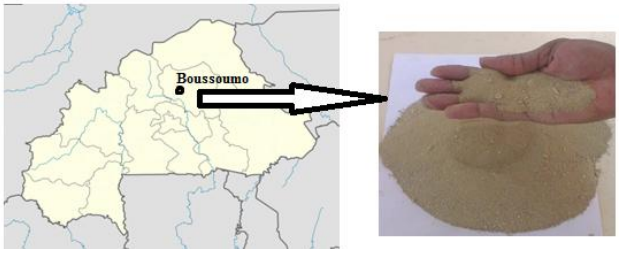

Figure 1. Location of the Tuff

2.1.2. Tuff

The Tuff used is a calcareous Tuff from the Boussouma quarry, a locality located in the north-central region of Burkina Faso (Figure 1). This Tuff was crushed in the laboratory by a ball mill and sifted through a 125 µm. The particle size analysis shown in Figure 2 shows that the median diameter D50 of the Tuff is 8.7 µm. However, the largest diameter being 125 µm, we have a D90 of 60.3 µm compared to 34.6 µm for cement. The chemical and physical characteristics of Tuff are given in Table 1. Its bulk density is 0.86 t/m^3, its specific density is 2.65 t/m^3. Tuff therefore has a lower density than the cement used. The chemical composition of Tuff determined by the Fluorescence X Spectrometry technique shows that the Tuff studied is composed of 82.55% silica, alumina and iron oxide. It is also noted that its glass content given by the difference between the crude silica and lime content is 57.9%. This value is greater than 34%. This suggests a predisposition to pozzolanic properties of Tuff de Boussouma according to ASTM C618. Table 1 also shows that the Tuff of Boussouma contains 2.5% lime and a fire loss of 7.18%. Due to its chemical composition, the Tuff studied in this work corresponds to a type N pozzolan according to ASTM C 618 standard.

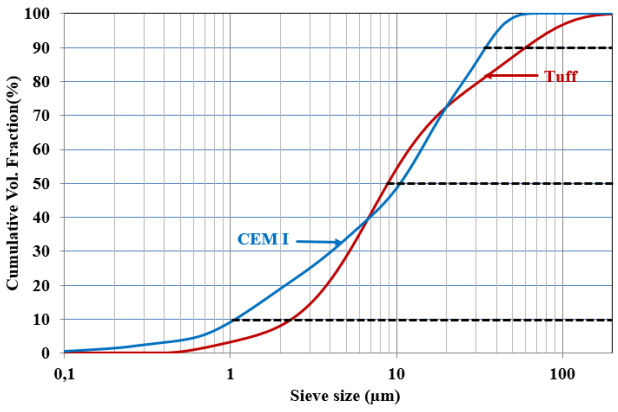

Figure 2. Particle size distribution of Cement and Tuff

The mineralogical composition of Tuff was obtained by X-ray diffraction on a non-oriented powder crushed at 125 µm. The result (Table 1 and Figure 3) shows that the major minerals are quartz, albite and muscovite.

2.1.3. Sand

The sand used to make the mortar is local sand with a maximum size of 5mm, an specific density of 2.7, an apparent density of 1.58 and an equivalent sand values between 88.58% and 90% in accordance with the standard (NF 18-EN 933-8 [18]). The granulometric analysis of the

sand was carried out in accordance with NF P 94-056 [19]. The results showed that the sand has a fineness of 1.27, a Hazen uniformity coefficient of 3.2 and a curvature coefficient of 0.8.

2.1.3. Superplasticizer

In order to ensure adequate workability of the different mortars formulated in this study, a high water-reducing superplasticizer was added to the mixing water. This is SIKA VISCOCRETE KRONO 30. It has a chloride content of minus 0.1%, a density of 1.11g/cm^3, a pH of 5.5 and an extraction percentage of 35%.

2.2. Experimental Methods

2.2.1. Sample Preparation and Mix Design

In order to study the effect of Tuff on the properties of mortar in the fresh and hardened state, mortars were prepared with a water to binder mass ratio (W/ B) of 0.27 for setting time test and 0.5 for all other tests. The sand to binder mass ratio is 3.0 according to the NF-EN 196-1 standard [19]. The Tuff was incorporated into the mortar in the following proportions: 0%, 10%, 15%, 20%, 25% and 30% by mass substitution of the cement. The detailed mix proportions of the mortars are shown in Table 2.

When preparing the mortars, sand, tuff and cement in different proportions (Table 2) are mixed for 2 minutes in an automatic mixer. Subsequently, the mixing water containing high water reducing superplasticizer agent is added to the mixture and mixed for 2 minutes. For semi adiabatic calorimetric and setting tests, the mixtures are made without the addition of superplasticizer.

For mechanical tests, prismatic specimens 40x40x160mm^3 are manufactured and for durability tests, cylindrical specimens (50mm diameter and 100mm height) are manufactured. The manufacturing, moulding and curing processes of the specimens comply with the requirements of EN 196-1 [19]. To avoid evaporation of water from the test specimen, the moulds are covered by a plastic film and stored for 24 hours in a regulated room at 20℃±2℃ and a relative humidity of 60%±5%. All specimens were removed from the moulds 1 day after casting. Thereafter, they were cured in lime saturated water in a container until the day of testing. The container being held in the regulated room.

2.2.2. Experimental Methods

The setting time corresponds to the time interval between the initial set and the final set. The setting time test is carried out on the different binder pastes (CEM I + T) using the automatic VICAT device in accordance with EN 196-3 [20].

A hydration heat measurement is carried out on blended mortars (CEM I + T). The test is carried out by semi-adiabatic Langavant calorimetry according to NF P 15-436 [21]. This test is performed in a controlled room at 20℃±2℃ temperature and 60%±5% relative humidity.

The total shrinkage of mortars is measured according to standard NF P 15-433 [22] standard on 40x40x160mm^3 specimens fitted with studs at their ends. Measurements start immediately after the demolding of the specimens according to the experimental set-up shown in Figure 4. Sample size variations are measured with a digital retractometer with accuracy ±0.001mm. The samples are kept in a room at 20℃±2℃ and 60%±5% RH and the test lasted 10 days.

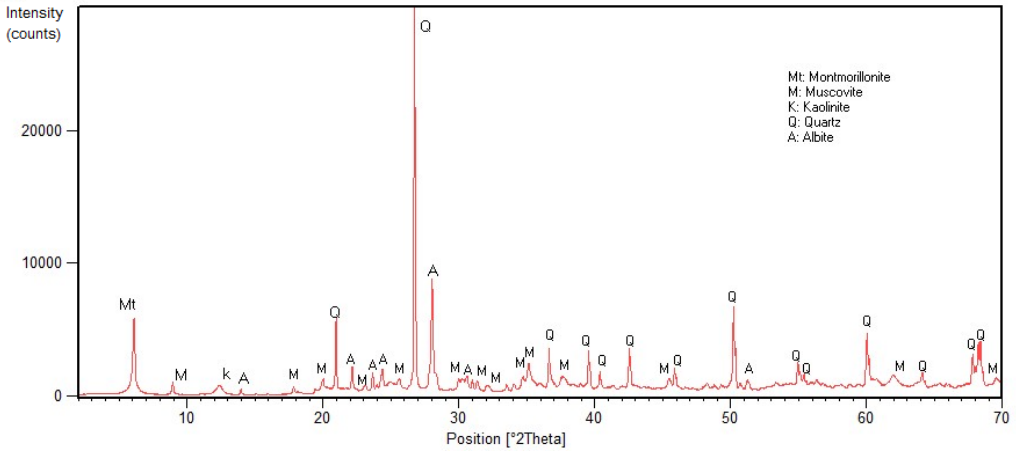

Figure 3. X-ray diffractogram of Tuff

Table 2. Mixing Proportions of the Different Tested Mortars

Substitution rate	Specimen testing (W/B=0.5 and A/B=1.5%)					Setting time (W/B=0.27)			Hydration heat (W/B=0.5)			
	C (g)	T (g)	S (g)	W (g)	A (g)	C (g)	T (g)	W (g)	C (g)	T (g)	S (g)	W (g)
0%T	450	0	1350	225	6.75	400	0	108	350	0	1050	175
10%T	405	45	1350	225	6.75	360	40	108	315	35	1050	175
15%T	382.5	67.5	1350	225	6.75	340	60	108	297.5	52.5	1050	175
20%T	360	90	1350	225	6.75	320	80	108	280	70	1050	175
25%T	337.5	112.5	1350	225	6.75	300	100	108	262.5	87.5	1050	175
30%T	315	135	1350	225	6.75	280	120	108	245	105	1050	175

C=Cement; B=Binder (C+T); T=Tuff; S=Sand; W=Water; A=Superplassticizer

Figure 4. Shrinkage measuring device

The prismatic specimens of 40x40x160 mm^3 of each formulation were split in two by a 3-point flexural test. The compressive strength test is conducted on both halves of the sample resulting from the flexural test. This test was carried out according to EN 196-1 with a press with a maximum capacity of 250 kN. Compressive strength is calculated using equation 1.

$$R_c = \frac{F_c}{b^2} \quad (1)$$

With b the lateral dimension of the specimen and Fc the breaking force at compression.

To study the durability of the mortars, three (3) series of tests were conducted: the capillary water absorption test, the acid attack test and the wet-dry cycle test.

The capillary water absorption rate was evaluated on cylindrical mortar specimens (50 mm x 100 mm) at 28 days of age as per PSAC-AFREM 199 standard [23]. The sample is brought into contact with water at a height of 5±1 mm and the mass variation is measured at 15mn, 30mn, 1h, 2h, 4h, 8h and 24h.

For the acid attack, 28-day-old cylindrical mortar specimens (40mm x 60mm) were immersed in a 5% concentration of sulphuric acid (H_2SO_4) solution. These specimens are removed after 1, 3, 7, 14 and 21 days of immersion to assess their mass loss after washing with water to remove the affected parts. The acid solution is renewed periodically to maintain a constant pH during the test.

The wetting and drying test was carried out in accordance with the requirements of ASTM D 559 [24]. The test is carried out on 50 mm x 100 mm cylindrical specimens which are subjected to simple compression tests after 12 wetting and drying cycles. A wet-dry cycle is an alternating immersion in water at 20℃ for 5 hours followed by drying in an oven at 71℃ for 42 hours.

3. Results and Discussion

3.1. Physical Characteristics

3.1.1. Initial and Final of Setting Times

The values of the initial set and final set time are shown in Figure 5. We note that the initial setting time of the cement increases with the substitution rate of CEM I by Tuff compared to the reference paste without Tuff. Several authors in the literature find similar results [25,26]. This behavior is attributed to the dilution effect resulting from the decrease in clinker content in mixtures. This involves less C_3S, which is the fastest clinker phase of hydration. However, the final setting time decreases with increasing Tuff content in the mixes and this could be explained by the presence of kaolinite in the Tuff, which would have contributed to making the pasta more viscous, especially since the Tuff content is high.

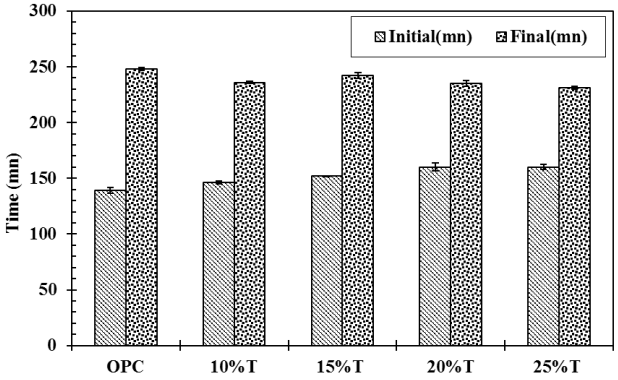

Figure 5. Shrinkage measuring device

3.1.2. Hydratation Heat

The results of the tests are shown in Figure 6. The maximum temperature rise was reached at 27.6 ℃ on the reference samples corresponding to a temperature of 42 ℃. A decrease in heating was noted with the increase the substitution rate of the CEM I by the Tuff. A heating difference of approximately 19% was observed between the mortar containing 30% of Tuff and the reference mortar. Sanchez et al., [27] and Brooks et al., [28] observed the same results. These authors explained their results by the dilution effect that could take precedence over pozzolanic reactions. In addition, Figure 6 shows that the substitution of Tuff decreases the time of attaining the maximum temperature. This result is in agreement with the reduction of the time of end of setting time on Vicat apparatus (Figure 5).

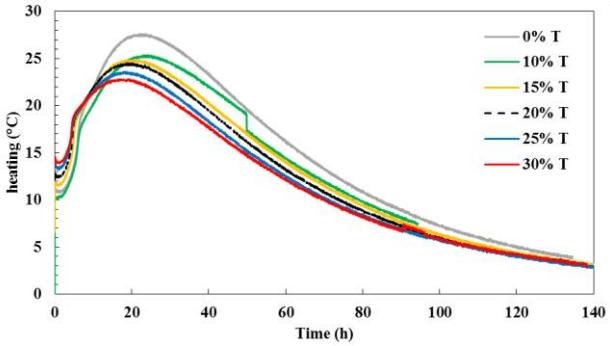

Figure 6. Evolution of the heating according to the substitution rate of the Tuff

3.1.3. Total Shrinkage

Figure 7 shows the evolution of the total shrinkage according to the substitution rate of the Tuff. For all the mortars examined, the total shrinkage is significant for the first 24 hours and its kinetics decrease thereafter. We note

a decrease in the total shrinkage of mortars with the increase in the Tuff rate. Thus, after 10 days, the total shrinkage is 1042 µm/m, 946 µm/m, 865 µm/m, 831 µm/m, 795 µm/m and 735 µm/m respectively for 0% T, 10% T, 15% T, 20% T, 25% T, 30% T. This result agrees with those in the literature [29,30] which showed that the addition of slow-acting pozzolanic additions reduces the shrinkage of mortars by increasing the size of the capillary pores, which would reduce the capillary pressure and therefore, the shrinkage. Yilmaz and Ucar [31] also reported similar results for Tuff (clinoptilolite) and attributed this to the reduction in water evaporation used for the formation of new hydrates.

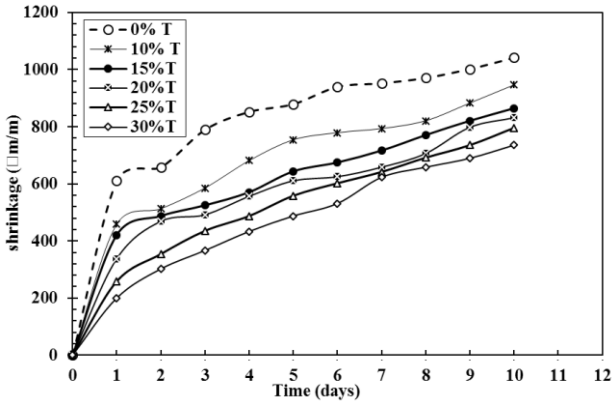

Figure 7. Effet of the Tuff on total shrinkage of mortars

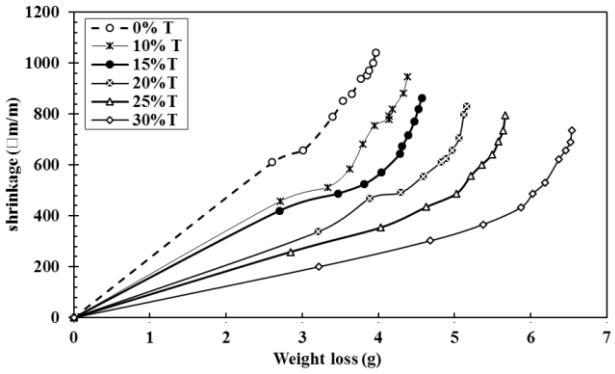

Figure 8. Shrinkage versus of weight loss

Figure 8 shows the results of the analysis of the total shrinkage according to the mass loss of the mortars. In this figure, it can be noted that for the same mass loss, the shrinkage is low for higher rates of Tuff. It can therefore be considered that there is an increase in the pore radius in the Tuff mortars, which contributes to reducing the capillary depression and thus the kinetics of the total shrinkage.

3.2. Compressive Strength

The evolution over time of the compressive strength of mortars is presented in Figure 9. There is a reduction in the compressive strength of mortars according to the substitution rates, whatever the age. This reduction is even higher than the substitution rate is greater than 15%. At these rates, the compressive strength of the mortars hardly changes between 14 and 56 days. This could be due to a dilution effect as a result of the substitution and the weak pozzolanic reaction of the Tuff used because of its low fineness. In addition, previous studies on the incorporation of Tuff in the mortar have shown that the pozzolanic reaction of Tuffs is observed in the long term [34]. In order to analyze the effect of the fineness of the Tuff used in this work, a study on compressive strength was discussed using a greater fineness (sieve less than 80 µm). It can be clearly seen in Figure 10 that at 28 days cure, the mortars formulated with Tuff max diameter of 80 µm had better results compared to mortars made with the Tuff max diameter of 125 µm. There is thus a 16% to 12% increase in compressive strength for the substitution rates of 10% and 15% respectively compared to the reference mortar. At 20% of substitution, the mortar containing Tuff has almost the same resistance as the reference mortar. These results confirm the influence of the fineness of the mineral additions on their pozzolanic reactivity. However, finer grinding requires higher energy expenditure.

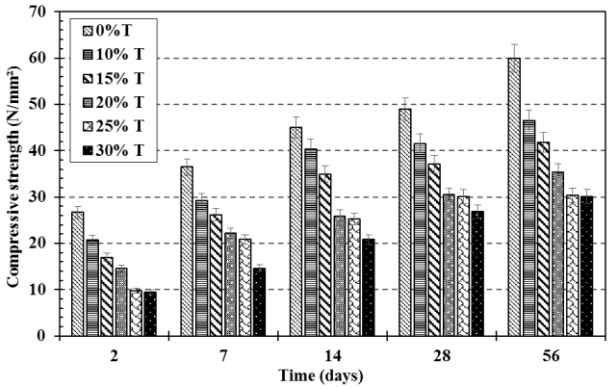

Figure 9. Evolution of compressive strength over time

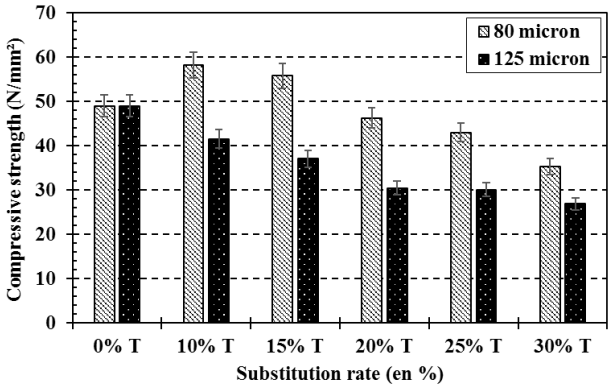

Figure 10. Influence of fineness on compressive strength at 28 days versus of substitution rates

3.3. Durability

3.3.1. Capillary Absorption of Water

Figure 11 shows that the mortars containing the Tuff generally have low capillary absorption capacities compared to the reference mortars (0% T). However, the study by Cherrach et al. [32] on the incorporation of Tuff in concrete as a partial substitution for ordinary sand has higher capillary absorptions than the reference. They explain this by the micropores that contain concretes with Tuff. Thus, the low absorption capacity of our mortars with the Tuff could be explained by the presence of larger

pores compared to the control mortar, which would reduce the capillary suction. At 8 hours immersion, the substitution of 15%, 25%, 30% T has the same values as the control mortar of the order of 3 kg/m². These values are similar to those obtained by Luc Courard [33] with the substitution of metakaolin for cement at 5, 10, 15 and 20%. The rate of 10% shows the lowest absorption at 8 hours.

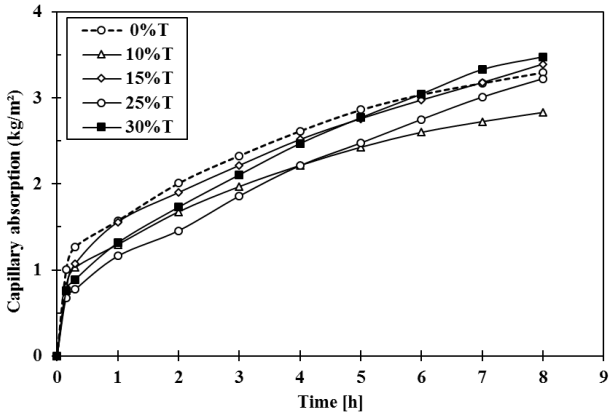

Figure 11. Influence of the addition of Tuff on the capillary absorption of motars

3.3.2. Wetting-Drying Cycles

Visual analysis of the samples that have undergone the wetting-drying cycles shows the existence of microcracks on the surface of the samples after the 12 cycles. Figure 12 shows the compression test results before and after the 12 cycles. It is noted that the mechanical strength after the cycles is almost the same as on the specimens before the cycles and whatever the rate of substitution. This result indicates that the use of Tuff as a partial substitution of the cement does not risk to degrade the behavior of the cementitious material during a wetting-drying cycle.

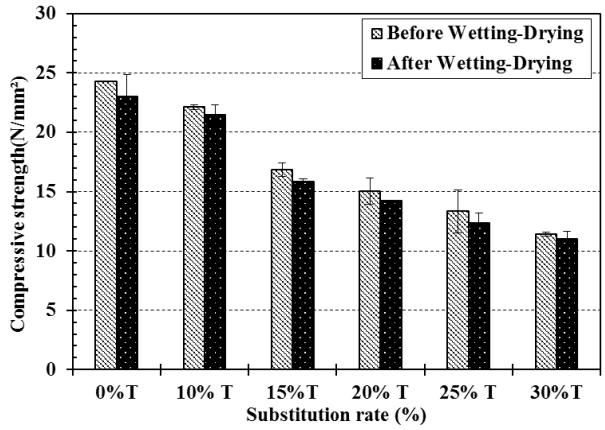

Figure 12. Influence of the variation of the temperature on the resistances of the mortars of Tuff

3.3.3. Acid Attack

Figure 13 shows the evolution of the relative weight loss of the studied samples immersed in 5% sulfuric acid during a period of 21 days. These results show that the loss of mass increases with immersion time regardless of the mortar considered. This loss of mass could be attributed to the leaching of the hydrates contained in the mortar by the acid during the period of exposure [34,35].

We note, however, that resistance to acid attack increases with the rate of CEM I substitutions by Tuff. According to the literature [36], this may be due to the fact that these mortars have low levels of portlandite which is the most soluble phase of hydrates. Indeed, the decrease of the CEM I rate, thus of clinker as well as the reaction between a part of the portlandite produced and the reactive alumina and silica of the Tuff would have contributed to decrease the rate of portlandite in the mortars containing the Tuff. The improvement in the acid attack resistance of Tuff-containing mortars is clearly shown in the photos of Figure 14.

The results also show that the severity of sulfuric acid attack gets more pronounced with time. This is explained by the fact that during the attack of sulfuric acid, in addition to the leaching phenomenon, there is formation of expansive ettringite in the pores of the mortar resulting in the appearance of cracks and hence, greater penetration of the aggressive solution [37,38].

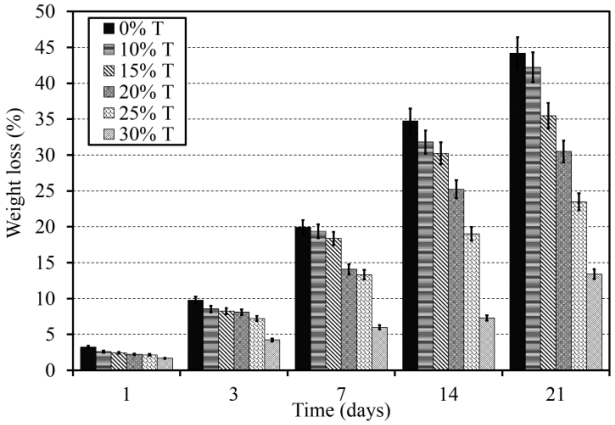

Figure 13. Evolution of mass loss of Tuff mortars versus the exposure time in sulfuric acid (H_2SO_4)

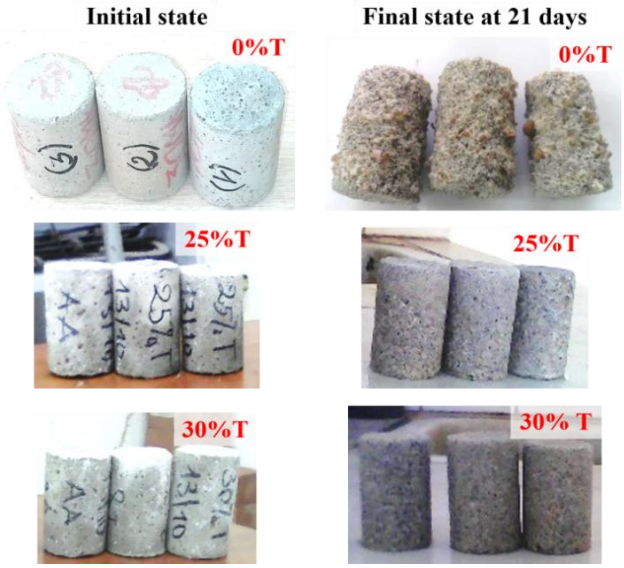

Figure 14. Visual aspect of degradation of Tuff mortars by (H_2SO_4)

4. Conclusion

From the experimental results of this study, the following conclusions can be drawn:

- On a physicochemical level, the incorporation of Tuff into the cement causes a set start delay but the end of set time is reduced when the Tuff rate increases. This last result is confirmed by the semi-adiabatic calorimetry test. Lower heating is also obtained for mortars containing the Tuff compared to the control mortar. Finally, the incorporation of the Tuff in the mortar causes a reduction in the total shrinkage.
- From the point of view of mechanical properties, the incorporation of Tuff at a particle size smaller than 125µm causes a decrease in compressive strength at all cure ages. With rates of 10% and 15%, there is a respective decrease of 15% and 24% compared to the reference mortar. Increasing the fineness of the Tuff (sieve less than 80 µm) makes it possible to increase the reactivity of the Tuff. This gives a 16% to 12% increase in compressive strength for the substitution rates of 10% and 15% respectively compared to the reference mortar.
- For durability, a Wetting-Drying test showed that Tuff mortars are not very vulnerable to sudden changes in humidity. The acid attack results expressed in terms of mass loss show that resistance to acid attack increases with increasing of Tuff rate.

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