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Assessment of the Durability Against a Chemical Attack of Fiber-Reinforced Lightweight Pouzzolanic Concrete under the Effect of Temperature

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ABSTRACT

The study of the durability of Fiber-Reinforced Lightweight Pouzzolanic Concrete (FRLPC) is a topic of research that focuses on evaluating the skills of FRLPC, because exposure to certain chemicals can cause deterioration and reduce the lifespan of the concrete. Chemical attacks can occur due to exposure to acids, sulfates, and other substances commonly found in the environment. The work presented here aims to analyze the influence of different types of fibers on the behavior of lightweight concretes (LWC) based on pozzolanic aggregates in aggressive media such as acids and under the effect of temperatures. The choice of pozzolanic aggregates is to valorize natural pozzolan as lightweight aggregates in concrete, knowing that this material is abundant in Algeria. In this sense, different tests have been carried out using metal, polyethylene, and polypropylene fibers in LWC manufactured with pozzolanic aggregates. The LWC specimens were kept in water saturated with lime until the age of testing (28, 60, and 90 days). Then, the specimens were subjected to heating under two temperatures (200°C and 600°C). After cooling, the specimens were exposed to hydrochloric acid (Hcl) and sulfuric acid (H_2SO_4) solutions (5% w/w). The evaluation of the durability of these concretes and the mechanical behavior was obtained by the measurement of the mass loss and the compressive strength.

1. INTRODUCTION

Lightweight concrete (LWC) is a type of concrete that is made with lightweight aggregates, such as expanded clay, shale, or slag. LWC is an important construction material that offers several benefits like reduced weight, which is significantly lighter than traditional concrete and makes it easier to handle and transport. This reduces the overall structural load on a building, which can lead to cost savings in the design and construction process [1]. LWC has excellent thermal insulation properties due to the air pockets within the lightweight aggregate [2]. This can help to reduce energy costs associated with heating and cooling a building, making it an attractive option for sustainable construction projects. LWC has good fire resistance due to its lower thermal conductivity, which helps to slow the spread of fire within a building. This can improve the safety of the building occupants in the event of a fire [3-6]. Despite being lightweight, LWC can be just as durable as traditional concrete. The use of high-strength lightweight aggregates can improve the mechanical properties of the concrete and make it resistant to wear and tear [7]. LWC is an environmentally friendly building material, as it requires less material to produce and can help to reduce the carbon footprint of a building. Using lightweight concrete (LWC) allows a great deal of design flexibility and results in some interesting cost savings, including lower weight stresses, less foundation support due to lower dead loads, higher durability than conventional concretes [8, 9], and even higher strength [10, 11]. Because of this, LWC might be recommended as a good alternative to normal weight concrete. The mechanical behavior of LWC has been the subject of numerous investigations. however, there is little information available on how high temperatures and chemical attacks affect LWC. Pozzolan is a lightweight aggregate (LWA) that has been successfully used in the production of concrete, and some authors have chosen to employ fibers to create lightweight structural concrete [12, 13].

LWA is crucial to the production of lightweight concrete [14, 15]. According to Ismael and Mohammed [16], codes that the LWA utilized must be consistent with a number of norms, including ASTM C330 [17], and its 28 day compressive strength must be at least 17 MPa with an LWAC density ranging from 1120 kg/m^3 to 1920 kg/m^3.

Cunha et al. [18] found that the inclusion of fibers reduces sagging, used four different types of fibers but when the fibers have large form factors the water requirement increases. The authors also discovered that increasing the fiber content has a negative impact on the compressive strength of fiber-reinforced concretes, but that the presence of more fibers in the material boosted the flexural strength. Throughout their useful lives, concrete structures are exposed to a variety of stresses, including mechanical, thermal, and chemical environments. The mechanical characteristics of structural concrete are often not significantly degraded by the service loads [12-19]. However, the material is vulnerable to numerous different types of harmful effects at high temperatures, such as those that may occur in a fire in a concrete structure. The porosity and permeability of the concrete often increase as a result of these defects [20].

The effects of fibers on the mechanical and physio-chemical characteristics of concrete at high temperatures were discussed in several research [21, 22]. A number of authors have reported on the impact of fibers on the flexural strength of concrete exposed to high temperatures (280℃) [23, 24].

According to Dupont and Vandewalle [25], fiber-reinforced concrete can be used to increase the performance of concrete structural members such as deep beams, columns, and floors on grade in terms of crack-reduction, toughness, and ductility. with a large volume of uniformly distributed fibers the concrete behaves better mechanically [26]. However, a decline in workability and uniform distribution is shown as fiber volume and length increase. Although concrete is a material that is frequently used, it may encounter aggressive media depending on the environment. Concrete constructions may suffer severe deterioration in these hostile settings [27, 28].

Acidic environments that are expected to be harmful to concrete begin with pure waters, and progress to fresh water, before ending with inorganic and organic acids, including wastewater [22-32]. LWC with polypropylene fibers has demonstrated good performance against acid attack when made from pozzolanic aggregates and reinforced with fibers [33].

It is necessary to study the effect of chemical attacks on lightweight fiber concrete under the effect of high temperatures for several reasons:

Chemical resistance is an important factor in the durability of concrete structures, as it can cause structural damage and reduce the lifespan of the structure. Understanding the effect of chemical attacks on lightweight fiber concrete can help to design more durable structures.

Lightweight concrete is often used in applications that require resistance to high temperatures, such as industrial furnaces or chimneys. Therefore, it is important to understand how these concretes react to high temperatures in the presence of chemical attacks.

Fibers are often used to reinforce lightweight concrete, but the effect of these fibers on chemical and high-temperature resistance is not well understood. Therefore, it is important to conduct studies to better understand this effect and develop more high-performance concrete.

In this work, three types of LWC have been made with pozzolanic aggregates reinforced with polyethylene, metallic and polypropylene fibers. The LWC cured in limewater were: i) exposed to high temperatures (200℃ and 600℃) and; ii) exposed to hydrochloric acid (Hcl) and sulfuric acid (H_2SO_4). The aim of this study is to investigate the effect on their physical and mechanical properties. The use of natural pozzolanic aggregates brings about a good improvement in the mechanical performances. the use of pozzolana as aggregates in lightweight concrete gives good performance on heat behavior knowing that these aggregates is of volcanic origin.

The organization of work will be as follows: we started with an introduction where we talked about lightweight concretes and their advantages, as well as the most recent research on the behavior of lightweight, concretes under the effect of temperature and under the effect of chemical attacks. Then the second part will be devoted to the materials used and the test methods. The results obtained following the tests carried out, to finish with a conclusion.

Studying the effect of chemical attacks on lightweight fiber concrete under the effect of high temperatures is necessary to improve the performance and durability of concrete structures used in harsh environments. This research can also help to develop more resistant and durable building materials for future projects.

Several researchers have studied the effect of chemical attacks on lightweight concretes, and many researchers have studied the effect of high temperatures on lightweight concretes, as indicated below in the introduction. However, few have dealt with the combined problem of effect of chemical attacks and the effect of high temperatures at the same time, and the originality of my work is the use of pozzolanic aggregates for the manufacture of lightweight concrete.

2. MATERIALS AND METHODOLOGY

The concrete composition and specimen's preparation are described below. The use of local Algerian materials aims to valorize these materials, which are available at a moderate cost.

2.1 Cement

For the manufacture of different types of concrete, we used portland cement type (CEM II/A-L 42.5N) from the cement works of Beni Saf in the western region of Algeria. The chemical composition of the cement is presented in Table 1.

Table 1. Chemical compositions of cement

Oxides	%
SiO_2	23.65
CaO	56.80
Al_2O_3	5.52
Fe_2O_3	3.22
MgO	1.03
SO_3	2.45
L.O.I. (loss on ignition)	2.42
Insolubles	4.6
Total	99.69

2.2 Pozzolanic aggregates

The pozzolanic aggregates (PA) used in this work come from the Bouhamidi quarry located in the western region of Algeria. Pozzolana aggregates are extracted in the form of rock whose diameter differs from 50 to 100 mm. The rocks are then grinded and separated to obtain the different granulometric fractions used in this work, namely pozzolanic sand 0/3, pozzolanic gravel 2/5, and pozzolanic gravel 3/8 (Figure 1).

Table 2. Oxide composition compositions of pozzolana

Oxides	% by mass
Na_2O	4.444
MgO	3.970
Al_2O_3	21.45
SiO_2	45.182
$P2O_5$	0.931
SO_3	0.771
K_2O	1.160
CaO	9.783
TiO_2	2.404
Fe_2O_3	9.241

(a) Pozzolanic gravel 3/8 (b) Pozzolanic gravel 2/5 (c) Pozzolanic sand 0/3

Figure 1. Pozzolanic aggregates

The particle size distribution was carried out according to the standard ASTM C33 [34] and the results of the aggregate fractions are presented in Figure 2.

The chemical composition determined by X-ray fluorescence (XRF) is given in Table 2.

The main physical characteristics of the pozzolana is given in Table 3.

X-ray diffraction (XRD) data for 2-Theta values in the range of 4°–60° were acquired for the purpose of analyzing the crystallographic structure of the pozzolana aggregate. The sample's potential crystalline phases were determined using the computer program Highscore Plus. In Figure 3, the XRD pattern is displayed. The pozzolana sample had three phases Analcime, Augite, and Quartz (commonly found in natural pozzolana).

Table 3. Physical characteristics of pozzolana

Physical Characteristics	Value
Absolute density (g/cm^3)	2.75 ±
Apparent volumetric mass (g/cm^3)	0.81 ±
Porosity (%)	54.2 ±
Absorption (%)	60 ±
Humidity (%)	2.51 ±

2.3 Fibers

The fibers used to prepare the various test pieces of the concretes are polypropylene fibers (PPF), metal fibers (MF), and polyethylene fibers (PEF) (Figure 4). Their properties are summarized in Table 4.

2.4 Composition of concrete

Different types of fibers were used to prepare the concretes. Table 5 lists the mix proportions of the concrete tested in this investigation (BLP: without fibers; BLPE: with polyethylene fibers; BLPM: with Metallic fibers; BLPP: with Polypropylene fibers).

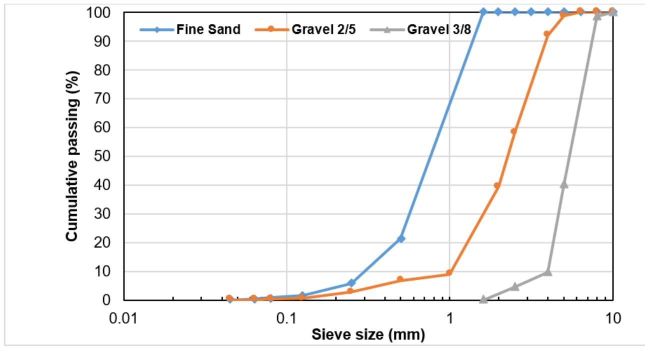

Figure 2. Particle size distribution of the different granular fractions

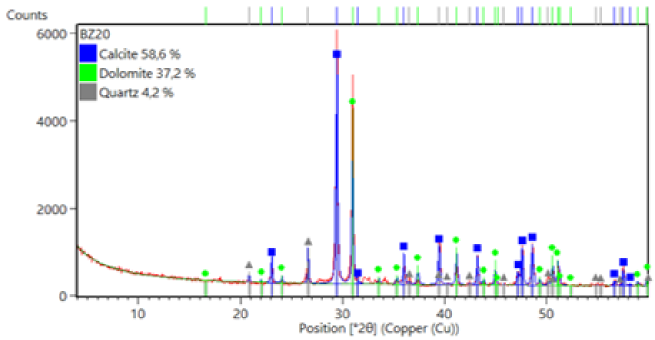

Figure 3. X-Ray diffractogram of the pozzolana

(a) Polypropylene fibers (PPF) (b) Metal fibers (MF) (c) Polyethylene fibers (PEF)

Figure 4. Types of fibers used

Table 4. Fibers characteristics

Type of fibre	Polypropylene (PPF)	Metal (MF)	Polyethylene (PEF)
Length (mm)	6	30	50
Diameter (mm)	0.05	0.5	0.3
Density (g/cm^3)	0.900	7.85	0.935
Tensile strength (MPa)	600	1700	350
Modulus of elasticity (GPa)	5-10	150-200	5

Table 5. Concrete mix

Concrete	BLP	BLPE	BLPM	BLPP
Cement (kg)	400	400	400	400
Sand (kg)	535	535	535	535
Gravel 2/5(kg)	248	248	248	248
Gravel 3/8(kg)	423	423	423	423
Water (L)	240	200	200	200
Adjuvant (%)	0	1.5	1.5	1.5
Fibers (%)	0	0.67	0.11	0.51
W/C	0.6	0.5	0.5	0.5

2.5 Test procedure

2.5.1 Heating–cooling tests

The specimens underwent heating-cooling cycles after demolding (see Figure 5). It was heated and cooled in accordance with RILEM standards [35]. A 1°C/min heating rate was maintained. The oven was shut off after the maximum temperature was achieved. To avoid thermal shock, specimens were allowed to cool down inside the oven.

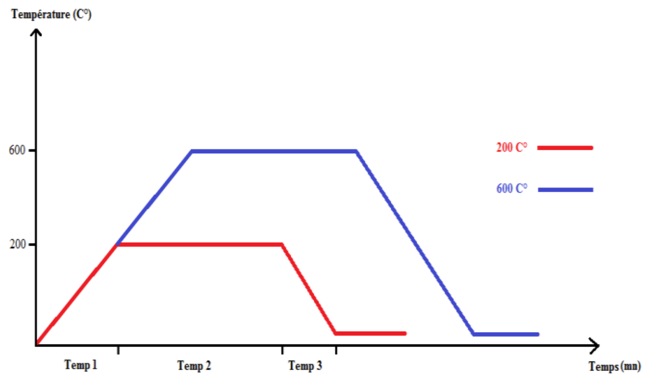

Figure 5. Heating-cooling cycles

2.5.2 Curing specimens

The samples were prepared in solutions of hydrochloric acid (Hcl) and sulfuric acid (H_2SO_4) with a concentration of 5% for each medium after 28 days of curing in lime-saturated water.

3. RESULTS AND DISCUSSION

3.1 Loss of mass

We used lost masses as a comparative parameter for the durability of our samples. The three samples chosen for this purpose were cleaned three times with distilled water to eliminate surface solution and mortar alterations before the mass loss measurements were done. To determine mass loss, we applied Eq. (1) as follows:

$$ML = \frac{(Mt - Mi)}{Mi} \times 100 \quad (1)$$

Whith *Mi*: mass initial (*g*) and *Mt*: mass (*g*) at time *t*.

In Figure 6, we can see, that the percentage of mass loss of the specimens which has passed into the furnace at a temperature of 600°C above which has passed at a temperature of 200°C of about 8 to 9%.

Figure 7 shows the results of the mass loss for the specimens under the temperature 200°C at the age of 7 and 28 days. We notice that the loss of mass evolves according to age and we can say that the concretes with base of the metal fibers have a weak mass loss at 7 days. However, at 28 days they have the biggest loss of mass from the alteration of concrete and fibers by chlorine knowing that chlorines attack metal fibers directly Lightweight concrete made from polypropylene fibers has good behavior with regard to hydrochloric acid. The presence of light pozzolanic aggregates contributed to the durability of these concretes in a strong acid medium such as hydrochloric acid (Hcl).

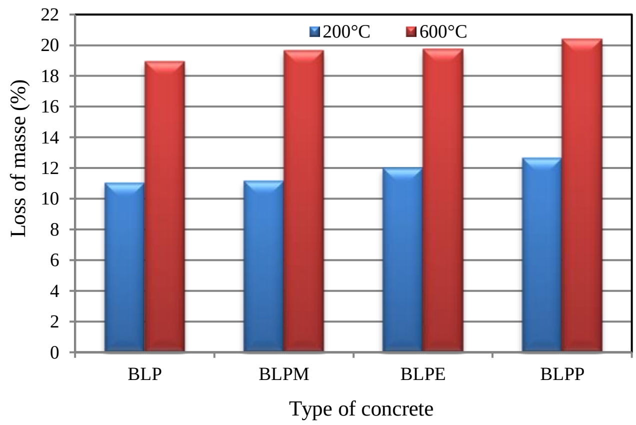

Figure 6. Mass loss of specimens after heat treatment

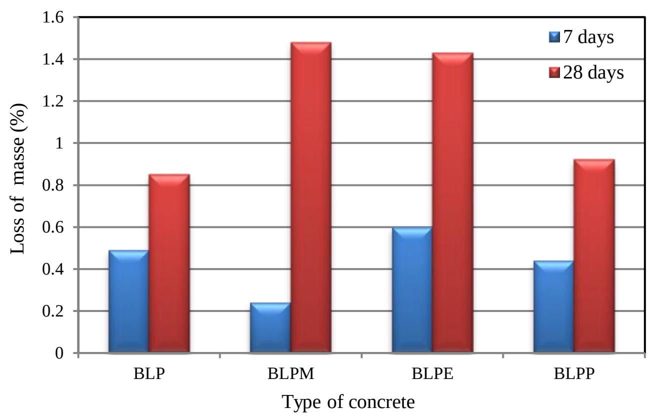

Figure 7. Loss of mass of specimens stored in acid (Hcl) according to the temperature 200°C

According to Navya and Rakesh [36], the addition of fibers in the concrete leads to a significant loss of mass for the specimens immersed in sulfuric acid and this, from the age at

14 days of the same for our results the loss of mass at 7 days is greater than at 28 days of age.

The results of mass loss of the different types of concrete under the temperature 600°C at the age of 7 and 28 days are shown in Figure 8, we note that the mass loss is quite significant at this temperature compared to those of 200°C. The specimens of lightweight concrete immersed in hydrochloric acid have suffered more degradation under this temperature, this is due primarily to the presence of cracks after heat treatment specimens. The microstructures of our concrete is severely degraded but the presence of pozzolanic aggregates that are of volcanic origin and can withstand high temperatures to achieve this result.

We also note that the specimens of lightweight pozzolanic concrete with polypropylene fibers and that of polyethylene fibers have more loss of mass because under high temperatures (600°C) the synthetic fibers will melt and leave room for open porosity that will help the penetration of aggressive agents. Concretes based on metal fibers have good behavior compared to other types of concrete.

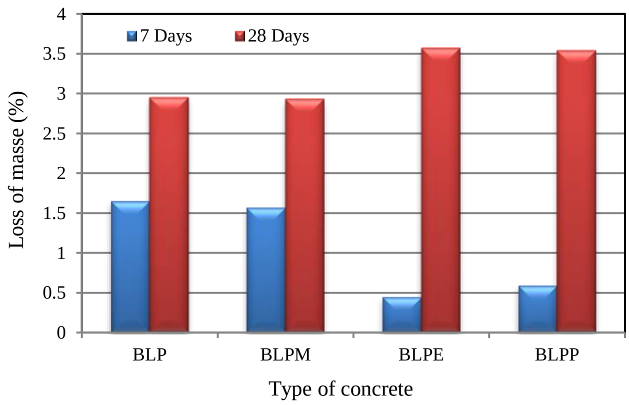

Figure 8. Loss of mass of specimens stored in acid (Hcl) according to the temperature 600°C

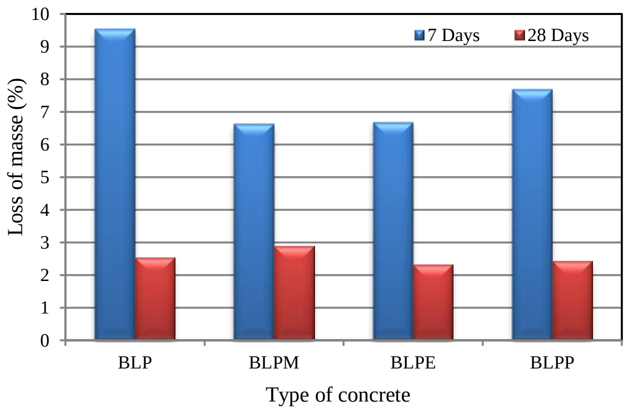

Figure 9. Loss of mass of specimens kept in sulfuric acid (H_2SO_4) as a function of temperature 200°C

In Figure 9, we find the specimens of concretes immersed for 7 days in a sulfuric acid solution after treatment of 200°C gave quite large mass losses compared to specimens at the age of 28 days. Knowing that sulfuric acid reacts with secondary gypsum in concrete to give rise to Ettringite expansive elements and very soluble hence the presence of white deposits on the specimens of concrete and acid solution; deformation of the test pieces is observed.

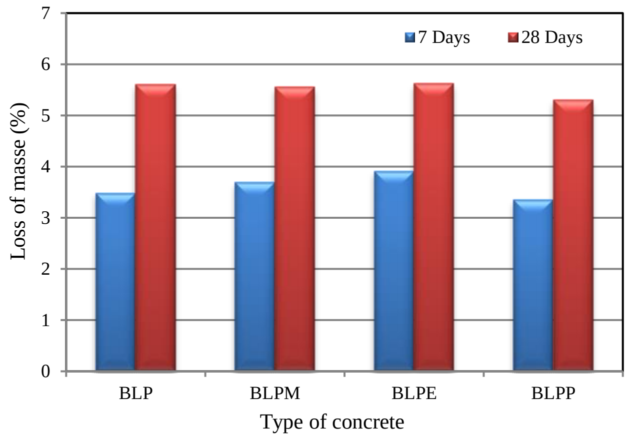

Figure 10. Loss of mass of specimens kept in sulfuric acid (H_2SO_4) as a function of temperature 600°C

Figure 10 results demonstrated that when concrete is subjected to sulfuric acid (*H_2SO_4*), there is a significant loss of mass. Calcium sulfate, which is created when sulfuric acid and calcium hydroxide mix (Eq. (2)), leads to accelerated deterioration because to sulfate attack. Below is an illustration of this process [37]:

$$H_2SO_4 + Ca\,(OH)_2 \rightarrow Ca\,(SO_4)2H_2O \quad (2)$$

The acid attack-induced dissolving of the calcium hydroxide happens in two stages. The reaction between the acid and calcium hydroxide in the cement paste is the first stage. This phase won't start until all of the calcium hydroxide has been consumed because the second phase is the hydrated calcium silicate acid reaction. In the most severe cases of acid attack, the dissolution of hydrated calcium silicate can significantly harm the concrete (see Figure 11 and Figure 12).

(a) Before (b) After

Figure 11. Test specimens stored in acid (H_2SO_4)

(a) Before (b) After

Figure 12. Test specimens stored in acid (*Hcl*)

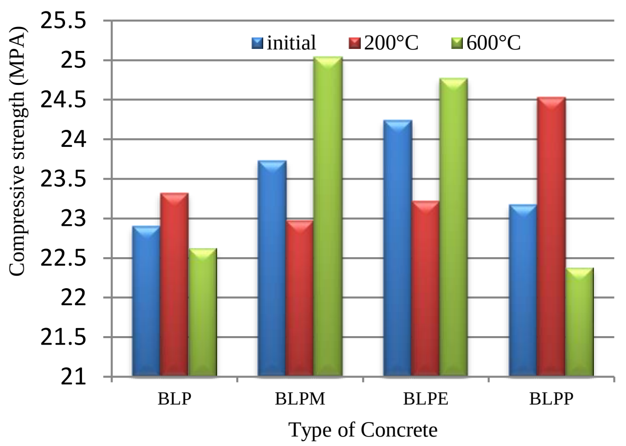

Figure 13. Compressive strength of specimens stored in water (7 days)

In Figure 13, we observe that there is an improvement of the concretes with fibers even under the effect of the temperature compared to the control concrete (initial), Ming et al. [38] observed the same results.

According to the work of Christidis et al. [39], using steel fibers increase the compressive strength, up to 42% compared to ordinary concrete. In our case, the greatest résistance is recorded with steel fibers concrete at 600°C. Similar results were observed by Serafini et al. [40] and cited by Yao et al. [41].

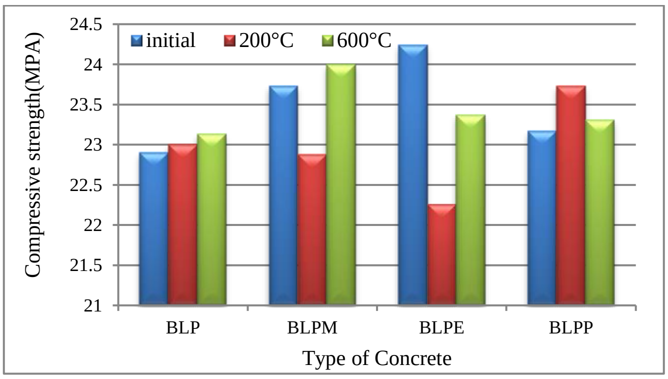

Figure 14. Compressive strength of specimens stored in water (28 days)

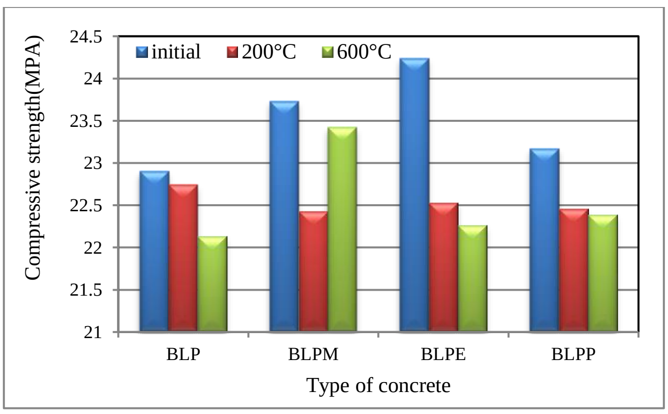

Figure 15. Compressive strength of specimens stored in H_2SO_4 (7 days)

To better understand the mechanical behavior of lightweight fiber-based concrete specimens, mechanical compressive strength tests are carried out, in which the fibers do not play an important role in the compressive strength but the fibers contribute to the tensile strength. The test specimens that we used are of size 7×7×7 cm^3, so we cannot use them for the tensile test.

The results of compressive strength obtained at the age of 28 days stored in water are resented in Figure 14, we observe that the compressive strength of BLPE concrete conserve in water is more important than the other concretes. The same behavior is mentioned by Shafigh et al. [42] and Hassanpour et al. [43].

Figure 15 illustrates the average compressive strengths at 7 days of specimens stored in H_2SO_4 , as in the previous figures, we see that the concrete BLPE has a higher resistance compared to the other concretes before heat treatment, but at the temperature of 600°C we have the BLPM concrete which has the greatest compressive strength. Zhang et al. [44] evaluated that polyethylene fibers were ineffective in preventing concrete from scaling at high temperatures. High thermal expansion of PP fibers before melting allows it to create micro cracks in concrete.

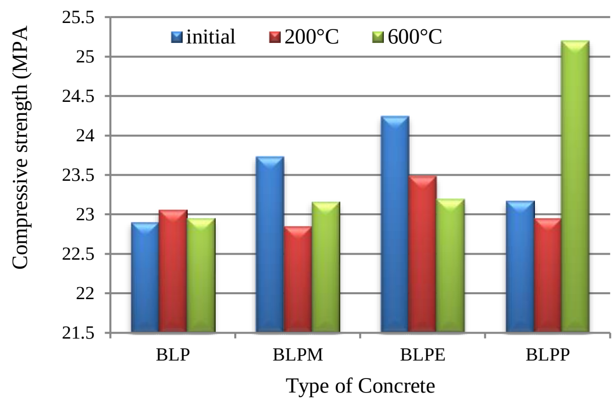

Figure 16. Compressive strength of specimens stored in H_2SO_4 (28 days)

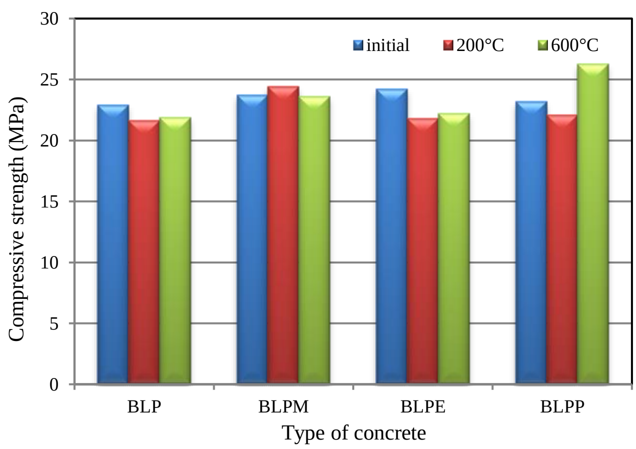

Figure 17. Compressive strength of specimens stored in Hcl acid at 7 days

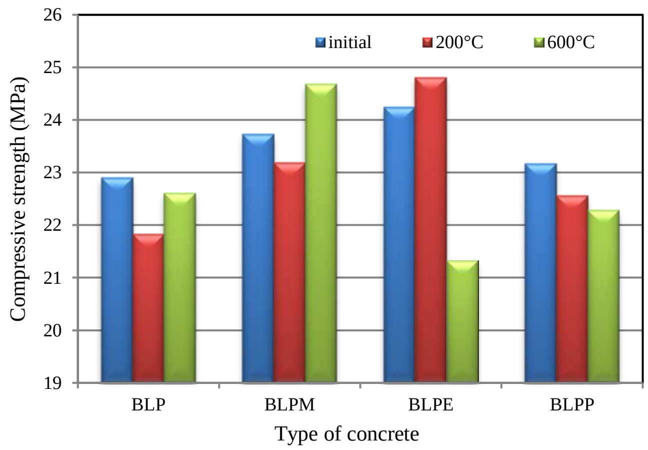

Figure 18. Compressive strength of specimens stored in Hcl acid at 2 years

In Figure 16, we observed another behavior for the specimens preserved in sulfuric acid at the age of 28 days, we have the concrete with polypropylene fibers (BLPP), which displays the greatest resistance in compression. Prinya et al. [45] found that using polypropylene fiber reduced the damage and improved the residual compressive strength of paste exposed to elevated temperatures. Other researchers also concluded that the compressive strength of concrete decreases with increasing exposure time to an acidic environment [46-47].

In Figures 17 and 18, we find the results of compressive strength obtained at the age of 7 and 28 days under the temperatures 200℃ and 600℃. We can see that we have a good result for polypropylene-based concrete with a resistance of 26 MPa so we can say that the Hcl acid did not really affect the resistance during 28 days of immersion. At 200℃ concretes with polyethylene fibers and those with metallic fibers have good strengths compared to other concretes.

4. CONCLUSION

The objective of this work was to make a contribution to the study of the durability of fiber-reinforced lightweight concretes based on pozzolanic aggregates under the effect of temperature, from several tests carried out on specimens exposed to different aggressive media.

The results obtained allow us to draw the following conclusions:

- The use of natural pozzolanic aggregates brings about a good improvement of the mechanical performances, for all the studied environments, the poorest behaviors are obtained for the solutions of 5% (H_2SO_4 and Hcl). Light concretes based on polyethylene fibers.
- Lightweight concretes immersed in sulfuric acid underwent a change in the outer facets with a total deformation of the specimens following the swelling due to the formation of Ettringite. The latter is totally soluble, hence the presence of white debris on the specimens of the concretes and in the sulfuric acid solution.

The purpose of heat treatment is to see the behavior of concretes under extreme conditions such as temperature rise or fire, the use of pozzolana as aggregates in lightweight concrete gives good performance knowing that these aggregates are of volcanic origin. The contribution of the fibers did not give good results for the compressive strength because their role-plays on the tensile strength. The absence of molds for carrying out the tests dedicated to this effect prevents us from better seeing the tensile strength. As a result of our work, we have been able to have a light concrete based on structural pozzolanic aggregates, i.e. it has good resistance to mechanical compression.

This study suggests that the durability of Fiber-Reinforced Lightweight Pouzzolanic Concrete (FRLPC) needs to be considered against chemical attacks in the presence of high temperatures. The managerial implications of this study are as follows:

The study highlights the need to consider the durability of FRLPC when it is exposed to chemical attacks under high temperatures, which is important information for managers involved in construction projects that use FRLPC.

To ensure the durability of the FRLPC constructions we need to choose carefully the components and create mixes that can survive chemical attacks and high temperatures. Take the necessary actions to prolong the lifespan of FRLPC structures by being aware of the upkeep and repair requirements of these structures, which are subject to chemical attacks and high temperatures. The study underscores the importance of testing and monitoring the performance of FRLPC structures over time to ensure that they remain durable and resilient in the face of chemical attacks and high temperatures.

REFERENCES

[1] Samui, P., Kim, D., Iyer, N.R., Chaudhary, S. (Eds.). (2020). New Materials in Civil Engineering. Butterworth-Heinemann.

[2] ASTM Committee C-9 on Concreate and Concrete Aggregates. (2017). Standard specification for lightweight aggregates for structural concrete. ASTM International.

[3] Dabbaghi, F., Tanhadoust, A., Nehdi, M.L., Dehestani, M., Yousefpour, H. (2022). Investigation on optimal lightweight expanded clay aggregate concrete at high temperature based on deep neural network. Structural Concrete, 23(6): 3727-3753. https://doi.org/10.1002/suco.202100694

[4] Štefan, R., Foglar, M., Fladr, J., Horníková, K., Holan, J. (2020). Thermal, spalling, and mechanical behaviour of various types of cementitious composites exposed to fire: Experimental and numerical analysis. Construction and Building Materials, 262: 119676. https://doi.org/10.1016/j.conbuildmat.2020.119676

[5] Dabbaghi, F., Dehestani, M., Yousefpour, H., Rasekh, H., Navaratnam, S. (2021). Residual compressive stress–strain relationship of lightweight aggregate concrete after exposure to elevated temperatures. Construction and Building Materials, 298: 123890. https://doi.org/10.1016/j.conbuildmat.2021.123890

[6] Rashad, A.M. (2018). Lightweight expanded clay aggregate as a building material–An overview. Construction and Building Materials, 170: 757-775. https://doi.org/10.1016/j.conbuildmat.2018.03.009

[7] Balgourinejad, N., Haghighifar, M., Madandoust, R., Charkhtab, S. (2022). Experimental study on mechanical properties, microstructural of lightweight concrete incorporating polypropylene fibers and metakaolin at high temperatures. Journal of Materials Research and Technology, 18: 5238-5256.

https://doi.org/10.1016/j.jmrt.2022.04.005
[8] Nadesan, M.S., Dinakar, P. (2018). Influence of type of binder on high-performance sintered fly ash lightweight aggregate concrete. Construction and Building Materials, 176: 665-675. https://doi.org/10.1016/j.conbuildmat.2018.05.057
[9] Amin, M., Tayeh, B.A. (2020). Investigating the mechanical and microstructure properties of fibre-reinforced lightweight concrete under elevated temperatures. Case Studies in Construction Materials, 13: e00459. https://doi.org/10.1016/j.cscm.2020.e00459
[10] Liu, X., Wu, T., Liu, Y. (2019). Stress-strain relationship for plain and fibre-reinforced lightweight aggregate concrete. Construction and Building Materials, 225: 256-272. https://doi.org/10.1016/j.conbuildmat.2019.07.135
[11] Wu, T., Yang, X., Wei, H., Liu, X. (2019). Mechanical properties and microstructure of lightweight aggregate concrete with and without fibers. Construction and Building Materials, 199: 526-539. https://doi.org/10.1016/j.conbuildmat.2018.12.037
[12] Hoseini, M., Bindiganavile, V., Banthia, N. (2009). The effect of mechanical stress on permeability of concrete: A review. Cement and Concrete Composites, 31(4): 213-220. https://doi.org/10.1016/j.cemconcomp.2009.02.003
[13] Belhadj, A., Mohammed, H., Mahi, A., Derbal, R., Aouane, R. (2017). Comportement des bétons légers fibrés à base des granulats pouzzolaniques vis-à-vis des milieux acides. In CFM 2017-23ème Congrès Français de Mécanique. AFM, Maison de la Mécanique, 39/41 rue Louis Blanc-92400 Courbevoie.
[14] Pla, C., Tenza-Abril, A.J., Valdes-Abellan, J., Benavente, D. (2018). Influence of microstructure on fluid transport and mechanical properties in structural concrete produced with lightweight clay aggregates. Construction and Building Materials, 171: 388-396. https://doi.org/10.1016/j.conbuildmat.2018.03.135
[15] Zhao, Y., Gao, J., Chen, F., Liu, C., Chen, X. (2018). Utilization of waste clay bricks as coarse and fine aggregates for the preparation of lightweight aggregate concrete. Journal of Cleaner Production, 201: 706-715. https://doi.org/10.1016/j.jclepro.2018.08.103
[16] Ismael, T.M., Mohammed, S.D. (2021). Structural performance of fiber-reinforced lightweight concrete slabs with expanded clay aggregate. Materials Today: Proceedings, 42: 2901-2908. https://doi.org/10.1016/j.matpr.2020.12.746
[17] ASTM Committee C-9 on Concreate and Concrete Aggregates. (2017). Standard specification for lightweight aggregates for structural concrete. ASTM International.
[18] Cunha, F.G., Sampaio, Z.L.M., Martinelli, A.E. (2021). Fiber-reinforced lightweight concrete formulated using multiple residues. Construction and Building Materials, 308: 125035. https://doi.org/10.1016/j.conbuildmat.2021.125035
[19] Norris, W.E., Naus, D.J., Graves III, H.L. (1999). Inspection of nuclear power plant containment structures. Nuclear Engineering and Design, 192(2-3): 303-329. https://doi.org/10.1016/S0029-5493(99)00125-9
[20] Noumowe, A.N., Siddique, R., Debicki, G. (2009). Permeability of high-performance concrete subjected to elevated temperature (600 C). Construction and Building Materials, 23(5): 1855-1861. https://doi.org/10.1016/j.conbuildmat.2008.09.023
[21] More, F.M.D.S., Subramanian, S.S. (2022). Impact of fibres on the mechanical and durable behaviour of fibre-reinforced concrete. Buildings, 12: 1436. https://doi.org/10.3390/buildings12091436
[22] Wu, C., Li, V.C. (2017). Thermal-mechanical behaviors of CFRP-ECC hybrid under elevated temperatures. Composites Part B: Engineering, 110: 255-266. https://doi.org/10.1016/j.compositesb.2016.11.037
[23] Choumanidis, D., Badogiannis, E., Nomikos, P., Sofianos, A. (2016). The effect of different fibres on the flexural behaviour of concrete exposed to normal and elevated temperatures. Construction and Building Materials, 129: 266-277. https://doi.org/10.1016/j.conbuildmat.2016.10.089
[24] Rudnik, E., Drzymała, T. (2018). Thermal behavior of polypropylene fiber-reinforced concrete at elevated temperatures. Journal of Thermal Analysis and Calorimetry, 131(2): 1005-1015. https://doi.org/10.1007/s10973-017-6600-1
[25] Dupont, D., Vandewalle, L. (2005). Distribution of steel fibres in rectangular sections. Cement and Concrete Composites, 27(3): 391-398. https://doi.org/10.1016/j.cemconcomp.2004.03.005
[26] Awoyera, P.O., Babalola, O.E. (2015). Influence of Steel and bamboo fibres on mechanical properties of high strength concrete. Journal of Materials and Environmental Science, 6(12): 3634-3642.
[27] Dubosc, A., Escadeillas, G., Blanc, P.J. (2001). Characterization of biological stains on external concrete walls and influence of concrete as underlying material. Cement and Concrete Research, 31(11): 1613-1617. https://doi.org/10.1016/S0008-8846(01)00613-5
[28] Santos, A.G., Rincón, J.M., Romero, M., Talero, R. (2005). Characterization of a polypropylene fibered cement composite using ESEM, FESEM and mechanical testing. Construction and Building Materials, 19(5): 396-403. https://doi.org/10.1016/j.conbuildmat.2004.07.023
[29] García-Vera, V.E., Tenza-Abril, A.J., Saval, J.M., Lanzón, M. (2018). Influence of crystalline admixtures on the short-term behaviour of mortars exposed to sulphuric acid. Materials, 12(1): 82. https://doi.org/10.3390/ma12010082
[30] Ortega, J.M., García-Vera, V.E., Solak, A.M., Tenza-Abril, A.J. (2019). Pore structure degradation of different cement mortars exposed to sulphuric acid. Applied Sciences, 9(24): 5297. https://doi.org/10.3390/app9245297
[31] Tulliani, J.M., Montanaro, L., Negro, A., Collepardi, M. (2002). Sulfate attack of concrete building foundations induced by sewage waters. Cement and Concrete Research, 32(6): 843-849. https://doi.org/10.1016/S0008-8846(01)00752-9
[32] Fedaoui-Akmoussi, O., Molez, L., Kaci, S., Jauberthie, R. (2015). Etude du comportement mécanique et de durabilité des bétons fibrés dans un milieu agressif. In Rencontres Universitaires de Génie Civil.
[33] Belhadj, A.H.M., Mahi, A. (2016). Study of durability of mortar reinforced by fibers in aggressive environments. In The 9th International Concrete Conference, Dundee, Scotland. https://discovery.dundee.ac.uk/ws/portalfiles/portal/18078009/Proceedings.pdf.
[34] ASTM C33. (2011). Standard Specification for Concrete Aggregates (ASTM C33/C33M–11a), ASTM

International, USA.
[35] TC, R. (1995). Test methods for mechanical properties of concrete at high temperatures–part 1: Introduction; part 2: Stress–strain relation: and part 3: Compressive strength for service and accident conditions. Mater Struct, 28(181): 410-414.
[36] Navya, K., Rakesh, S. (2022). Studies on the effects of basalt fibres on the durability characteristics of high strength self compacting concrete. Materials Today: Proceedings, 60: 253-258. https://doi.org/10.1016/j.matpr.2021.12.512
[37] Tixier, R., Mobasher, B. (2003). Modeling of damage in cement-based materials subjected to external sulfate attack. I: Formulation. Journal of Materials in Civil Engineering, 305.
[38] Ming, X., Cao, M., Lv, X., Yin, H., Li, L., Liu, Z. (2020). Effects of high temperature and post-fire-curing on compressive strength and microstructure of calcium carbonate whisker-fly ash-cement system. Construction and Building Materials, 244: 118333. https://doi.org/10.1016/j.conbuildmat.2020.118333
[39] Christidis, K.I., Badogiannis, E.G., Mintzoli, C. (2021). Flexural behaviour of pumice lightweight concrete reinforced with end-hooked steel fibres. Structures, 33: 3835-3847. https://doi.org/10.1016/j.istruc.2021.06.090
[40] Serafini, R., Dantas, S.R., Agra, R.R., de la Fuente, A., Berto, A.F., de Figueiredo, A.D. (2022). Design-oriented assessment of the residual post-fire bearing capacity of precast fiber reinforced concrete tunnel linings. Fire Safety Journal, 127: 103503. https://doi.org/10.1016/j.firesaf.2021.103503
[41] Yao, X., Pei, Z., Zheng, H., Guan, Q., Wang, F., Wang, S., Ji, Y. (2022). Review of mechanical and temperature properties of fiber reinforced recycled aggregate concrete. Buildings, 12(8): 1224. https://doi.org/10.3390/buildings12081224
[42] Shafigh, P., Mahmud, H., Jumaat, M.Z. (2011). Effect of steel fiber on the mechanical properties of oil palm shell lightweight concrete. Materials & Design, 32 (7): 3926-3932. https://doi.org/10.1016/j.matdes.2011.02.055
[43] Hassanpour, M., Shafigh, P., Mahmud, H.B. (2014). Mechanical Properties of structural lightweight aggregate concrete containing low volume steel fiber. Arabian Journal for Science and Engineering, 39(5): 3579-3590. https://doi.org/10.1007/s13369-014-1023-9
[44] Zhang, D., Liu, Y., Tan, K.H. (2021). Spalling resistance and mechanical properties of strain-hardening ultra-high performance concrete at elevated temperature. Construct Build Mater, 266: 120961. https://doi.org/10.1016/j.conbuildmat.2020.120961
[45] Prinya, C., Thammanun, B., Apivich, P., Wunchock, K. (2021). Effect of elevated temperature on polypropylene fiber reinforced alkali-activated high calcium fly ash paste. Case Studies in Construction Materials, 15: e00554. https://doi.org/10.1016/j.cscm.2021.e00554
[46] Koushkbaghi, M., Kazemi, M.J., Mosavi, H., Mohseni, E. (2019). Acid resistance and durability properties of steel fiber-reinforced concrete incorporating rice husk ash and recycled aggregate. Construction and Building Materials, 202: 266-275. https://doi.org/10.1016/j.conbuildmat.2018.12.224
[47] Attiogbe, E.K., Rizkalla, S.H. (1988). Response of concrete to sulfuric acid attack. ACI Materials Journal, 85(6): 481-488. https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=0c9a841e53259b5ee01cff9171d2159752a0411f.