

EXPERIMENTAL CHARACTERIZATION OF THE MECHANICAL PROPERTIES OF CONCRETE BASED ON GLASS-POWDER

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ABSTRACT:

Annually, there is an enormous amount of glass waste created worldwide, yet only a small portion of that material is recycled. Recovering waste glass (WG) in concrete demonstrates excellent progress in lowering the amount of glass. Researchers have found that adding waste glass to concrete improves its qualities; WG can be utilized as powder, fine as well as coarse aggregate. However, the question that arises is how this powder added to concrete improves, or at least maintains, the mechanical properties of the concrete despite the reduction in the cement quantity. The aim of the present paper is to investigate the behavior of concrete with the addition of glass powder. For this purpose, a control concrete and concretes were prepared with 10%, 15% and 20% of the cement content of the glass powder, based on the same concrete formulation and by varying the W/C ratio. In the hardened state, the addition of glass powder up to 20% of the cement content, generated an increase in compressive strength at 28 days; this increase is caused by the reaction between the glass powder and the lime released during the hydration of Portland cement and creates a binder called hydrated calcium silicate (S-C-H) (pozzolanic reaction). The latter plays an important role in increasing the strength of concrete, and since the fineness of the glass powder is similar to that of cement, it has a role of filling, and accelerates the pozzolanic reaction. For an addition of 20% to 30% of pozzolan, theoretically we could react all the lime produced by the hydration of Portland cement. Therefore, beyond 25% or 30% of the glass powder, the strength is affected, which has been confirmed by many researchers. Finally, it can be concluded that the use of glass powder in concrete improves its mechanical behavior compared to ordinary condition, but with a limited percentage of 20% of the cement content.

1. INTRODUCTION

Concrete is increasingly being made with recycled and solid waste materials to address environmental problems and conserve energy (Kemer, Bouras, Mesboua, et al. 2021, Mesboua et al. 2021, Aissa et al. 2022). Engineers are now concerned with the sustainability of concrete as a building material in order to better understand the significance of environmental protection and resources conservation. Additional research into the green concrete technology is sparked by the improvement in concrete properties as well as the environmental benefits of using waste materials (Amin et al. 2021). A variety of solid waste materials, including building and demolition waste (Abed, Nemes, and Tayeh 2020, Tayeh, Al Saffar, and Alyousef 2020), marble waste (Marvila et al. 2019), fly ash (Al-Sodani et al. 2021), silica fume (Tawfik et al. 2021), metakaolin (Shahidan et al. 2017), rock waste (de Azevedo et al. 2021, Marvila et al. 2020), plastic waste (Almeshal et al. 2020), and ornamental stone waste (Carvalho et al. 2014) are available as alternatives and have been incorporated into concrete and mortar to develop their features, store energy, and reduce greenhouse gas emissions (Hamada et al. 2020).

Disposal of waste glass (WG) is regarded as a major environmental problem on a global scale. Over a million tons of glass wastes are created worldwide each year. Due to this

waste's lengthy degradation process, the environment is seriously threatened. Therefore, it is advantageous to recycle waste glass for use as aggregate or any other supplementary construction material. Utilizing glass waste would promote sustainable waste management, preserving natural aggregate and similar cementitious materials and assisting in environmental protection. Numerous studies focused on the use of used glass as a cement or aggregate substitute (Mageswari and Vidivelli 2010).

The technology of concrete incorporating crushed glass waste is part of a sustainable development approach. Indeed, this technology allows participating in the protection of the environment by the recovery of glass waste thrown to nature, which will be crushed and used as an alternative cementitious addition to concrete. In addition, the introduction of glass powder in concrete leads to improve its mechanical properties and reduce the use of cement in the composition of concrete. Therefore, this technique has an environmental, technological and economic aspect.

The idea of introducing glass powder in the concrete formulation as a replacement for 20% of cement is of great interest, as it is a major advantage from the economic and ecological viewpoint. Indeed, the production of cement is mainly responsible for the polluting character of concrete. Each

ton of cement produced is equivalent to approximately one ton of greenhouse gas emissions (Niang et al. 2013).

The incorporation of glass powder in concrete is rather new in the research field, there have been few tests performed on the structural element directly. Compressive strength tests were performed on cores of a concrete slab incorporating glass powder by Shayan et al (Shayan and Xu 2006).

We treated in this part of study, the influence of the valorization of glass powder in the composition of the concrete through the experimental characterization of the mechanical properties from the various concretes incorporated glass powder. From experimental test results, we try to distinguish the best behavior of cement-based concrete and glass powder through the studied properties of the different tested concretes; namely: the slump at the Abrams cone and the mechanical strength.

2. EXPERIMENTAL TESTS

To carry out this experimental work, we have presented, in the first phase, the constituent materials of the concrete through the identification of their characterizations, then, we have opted for the suitable formulation of the different concretes to be elaborated (control concrete, concrete of 10%, 15% and 20% of glass powder) by varying the E/C ratio. In the second stage, we proceeded to the manufacture of the various concretes and characterize their behavior in the fresh state, this phase was finalized by the conservation of the standardized cylindrical specimens 16-32 cm which were preserved after demolding in a thermostatic bath at 20°C during 28-days. The third and last section was the assignment of uni-axial compression tests on the standardized cylindrical specimens 16-32 cm.

2.1 Characterization of the used materials

2.1.1 Cement: The used cement is the Portland-cement CEM II/B 42.5 coming from ACC factory of LAFARGE-ALGERIA which mineralogical composition as well as chemical composition and physico-mechanical characteristic of cement are presented respectively in tables 1 and 2.

Phases	C ₃ S	C ₂ S	C ₃ A	C ₄ AF	CaO .L	Gypsum	Lime
(%)	57	19	05	13	01	05	18

Table 1. Mineralogical composition of cement

Chemical composition	(%)	Physical characteristics
SiO ₂	18.13	Initial setting time (mins): 150 – 180 min
Al ₂ O ₃	4.42	Final setting time (mins): 3 h 30 – 4 h 30
Fe ₂ O ₃	3.03	Specific gravity : 3.1 g/cm ³
CaO	60.78	SSA : 3 555 cm ² /g
MgO	1.84	Heat of hydration: 456.60 (j/g)
SO ₃	2.34	Compressive strength (MPa)
K ₂ O	0.64	7-d : 36.74
Na ₂ O	0.13	14-d : 41.07
P ₂ O ₅	0.10	28-d : 45.07
TiO ₂	0.23	
Loss on ignition	8.36	

Table 2. Chemical composition and physical-mechanical characteristics of cement

2.1.2 Sand: For the preparation of the different concretes, we used the rolled sand 0/5 of Oued Khemis Meliana with a

fineness modulus (FM = 2.72). Table 3, summarizes the physical characteristics of the sand to use.

Sand type	Absolute density (t/m ³)	Bulk density (t/m ³)	ESP (%)	FM
Rolled sand 0/5 of Oued Khemis Meliana	2.63	1.55	70	2.72

Table 3. Physical characteristics of sand

2.1.3 Aggregates: The gravels used in the composition of the various concretes are crushed gravels 3/8, 8/15 and 15/25 from

the quarry Azrou Keddara. The physical characteristics of these gravels are presented in Table 4.

Gravel type	Absolute density (t/m ³)	Bulk density (t/m ³)	Los Angeles for the granular class 10/14
Crushed gravel 3/8 from Azrou quarry Keddara	2.62	1.37	28
Crushed gravel 8/15 from Azrou quarry Keddara	2.63	1.41	
Crushed gravel 15/25 from Azrou quarry Keddara	2.64	1.43	

Table 4. Physical characteristics of gravel

The results of the particle size analysis of the aggregates by dry method according to the NF EN 932-2 standard are represented in figure 1:

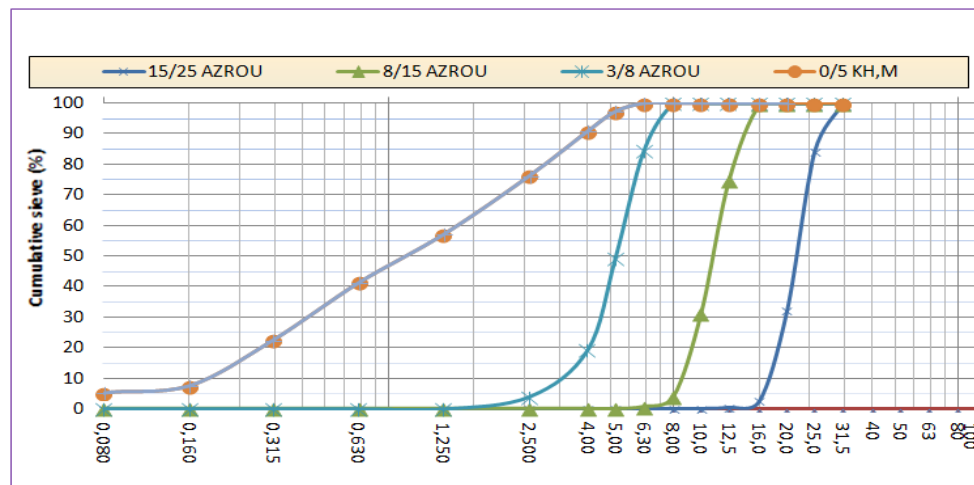


Figure 1. Dry sieve analysis of aggregates NF EN 932-2

2.1.4. Mixing water: The used water to produce the different concretes is tap water, we took the precaution of checking its cleanliness and its smell, and visually it appeared good to be used.

2.1.5 Glass powder: Coming from broken flat glass, glass powder is obtained after grinding the collected glass debris; the

grinding takes 1 hour to achieve a similar fineness as cement (Figure 2). The use of glass powder with fineness similar to that of cement can improve the mechanical characteristics of concrete. Generally, glass is mainly composed of amorphous silica.

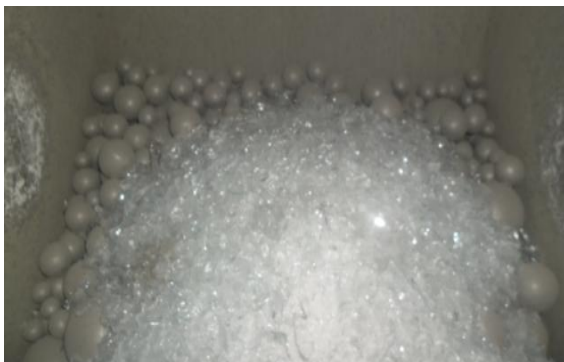


Figure 2. Crushing of waste glass

Recently, studies have been conducted on the use of glass as a pozzolanic material in the cement industry. These studies have shown that very fine glass particles with a size of less than 38 μm , can improve the mechanical properties of concrete due to the pozzolanic reaction of glass (Shao et al. 2000). In the other hand, chemical analysis is done using X-ray fluorescence

(XRF). Physical properties, specific gravity and Blaine fineness were determined using a pycnometer and Blaine permeability meter respectively. The chemical composition and physical characteristics of the glass powder are shown in Tables 5 and 6 respectively.

Component	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	K ₂ O	Na ₂ O	P ₂ O ₅	TiO ₂	LOI
%	72.84	0.98	0.55	9.66	1.76	0.25	0.43	12.69	0.01	0.04	0.79

Table 5. Chemical composition of the glass powder

Characteristics	
Specific gravity	2.57
Blaine fineness (cm ² /g)	4400
color	White

Table 6. Physical characteristics of the glass powder

The particle size analysis of the glass powder is shown in Figure 3. The mineralogical analysis of the glass powder by XRD is shown in Figure 4.

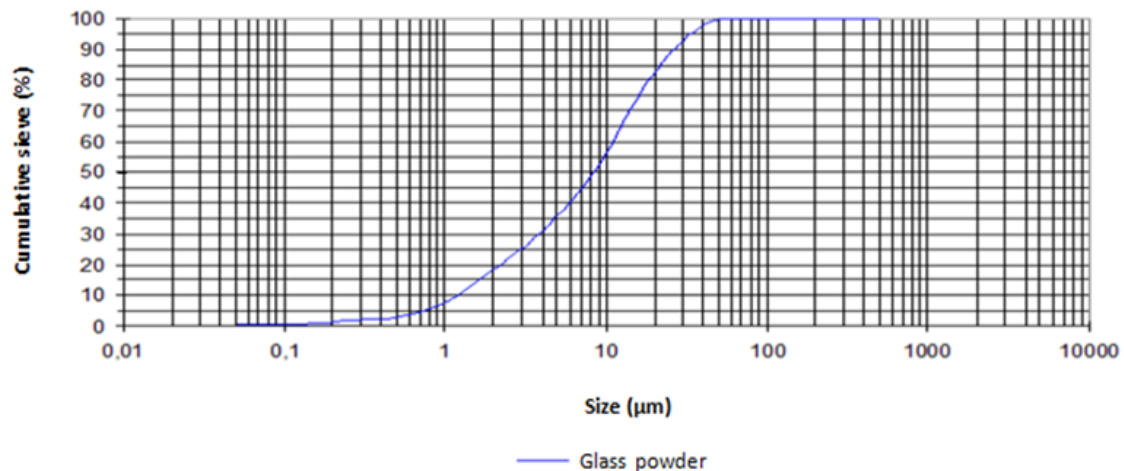


Figure. 3. Particle size analysis of the glass powder

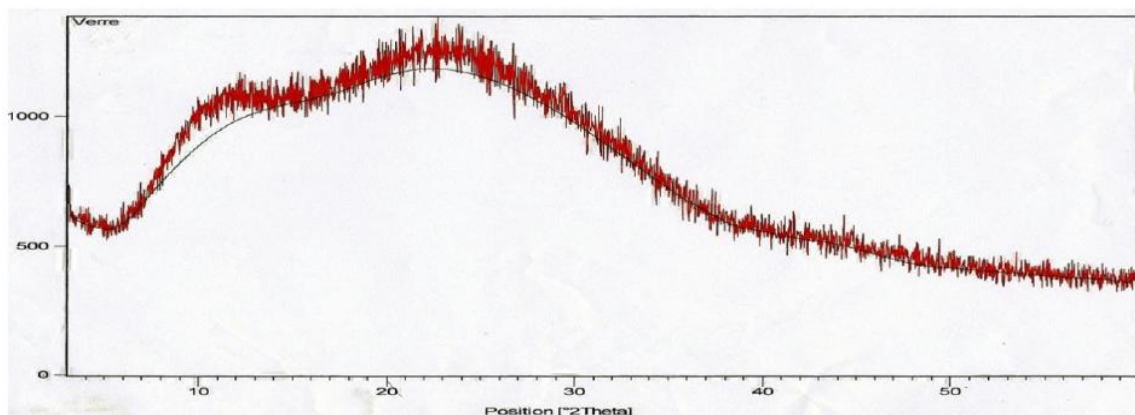


Figure. 4. X-ray image of the glass powder

2.2 Formulation of the tested concretes

2.2.1 Formulation of the control concrete: The quantities of the components of the control concrete shown in table 7 were determined using the Dreux Gorisse mix design method, which

consists of jointly finding the desired compressive strength and workability from essential basic data for the concrete mix design such as the size of the aggregates (D).

Materials	Unit	Control concrete
W/C=0.5		
Sand 0/5	Kg/m ³	724
Gravel 3/8	Kg/m ³	162
Gravel 8/15	Kg/m ³	559
Gravel 15/25	Kg/m ³	360
Cement CEM II/B 42.5	Kg/m ³	400
Water	L/m ³	200

Table 7. Control concrete composition

2.2.2 Formulation of concretes incorporated with glass powder: It is clear that the Dreux-Gorisse method is not adapted, because it does not take into account the different additions. For the concretes incorporated with glass powder, their formulations refer to the control concrete. The incorporation of the glass powder in the different concretes was carried out by substitution of the percentages of cement of 10%,

15% and 20% by fixing the ratio W/B, in the first case, to 0.5 of which B is the binder including the cement and the glass powder, therefore, the glass powder (GP) was considered as a binder in this case (Table 8). In the second case, we set the W/C ratio to 0.5, i.e., the glass powder, in this case, was considered as an addition (Table 9).

Materials	Unit	Concrete-10% of GP	Concrete-15% of GP	Concrete-20% of GP
W/B=0.5				
Sand 0/5	Kg/m ³	724	724	724
Gravel 3/8	Kg/m ³	162	162	162
Gravel 8/15	Kg/m ³	559	559	559
Gravel 15/25	Kg/m ³	360	360	360
Cement CEM II/B 42.5	Kg/m ³	360	340	320
Glass powder (GP)	Kg/m ³	40	60	80
Water	L/m ³	200	200	200

Table 8. Composition of the concretes with incorporated glass powder (W/B=0.5)

Materials	Unit	Concrete-10% of GP	Concrete-15% of GP	Concrete-20% of GP
W/C=0.5				
Sand 0/5	Kg/m ³	724	724	724
Gravel 3/8	Kg/m ³	162	162	162
Gravel 8/15	Kg/m ³	559	559	559
Gravel 15/25	Kg/m ³	360	360	360
Cement CEM II/B 42.5	Kg/m ³	360	340	320
Glass powder (GP)	Kg/m ³	40	60	80
Water	L/m ³	180	170	160

Table 9. Composition of concretes incorporated with glass powder (W/C=0.50)

2.3 Fresh state

2.3.1 Batch preparation: The mixtures of the various concretes were prepared using a planetary mixer (Figure 5).



Figure 5. Planetary movement mixer

To ensure a good homogeneity of the different concretes, we have opted for the following mixing sequence:

- First, check the number and condition of the cylindrical test specimens required for the tests. These should be greased with oil to facilitate demolding (see Figure 6);
- Assemble all the necessary material to carry out the tests;
- Check that the materials are not wet, otherwise dry them beforehand in the oven;
- prepare the amount of necessary water for the batch;
- Weigh the dry materials (gravel, sand, cement and glass powder) and introduce them into the mixer;
- Turn on the mixer to homogenize the dry mixture over 30 seconds;
- Leave the mixer running and gradually add the mixing water;
- Carry out the tests immediately after stopping the mixing, the tests were carried out at least twice to validate the obtained value ;
- The cylindrical specimens in two/three layers without vibration.



Figure 6. Lubricated Cylindrical test moulds

2.3.2 Fresh concrete test

2.3.2.1 Abrams cone test:

a. Test principle: This test (Kemer, Bouras, Sonebi, et al. 2021, Kemer 2022) consists in measuring the slump height of a truncated cone-shaped volume of fresh concrete. The latter is compacted in a mould having a shape of truncated cone. When the cone is lifted vertically, the slump of the concrete allows measuring its consistency.

b. Equipment: Mould: made of metal, minimum thickness 1.5 mm. The inner wall of the mould must be smooth, without roughness. The mold shall be shaped like a hollow truncated cone (Figure 7) with the following internal dimensions:

- Base diameter: (200 ± 2) mm,
- Top diameter: (100 ± 2) mm,
- Height: (300 ± 2) mm.

The mould must be equipped with two handles at the top and fixing or support legs at the bottom in order to immobilize it.

- Pricker rod: circular, straight, made from steel, (16 ± 1) mm in diameter, and (600 ± 5) mm in length, with rounded ends.
- Funnel (optional): Made of non-absorbent material not directly attackable by the cement paste, having a device to

allow the funnel to be properly placed on the mold specified above.

- Ruler: Graduated from 0 mm to 300 mm, with 5 mm graduations, the zero being located at one end of the ruler.
- Base surface or tray: Tray or other surface, rigid, flat, non-absorbent, on which the mold will be placed.
- Re-homogenization container: Flat tray of rigid structure, made of non-absorbent material and not directly attackable by the cement paste. Its dimensions must be appropriate so that the concrete can be easily re-mixed with the square shovel.
- Square shovel: The square shaped shovel is required to ensure proper mixing of the material on the material on the re-homogenization container.
- Timer or clock: Capable of measuring time to within 1 second.



Figure 7. Abrams cone

c. Procedure:

- Humidify the mold and the base tray, and then place the mold on the tray.
- Hold the mold firmly in place during filling, securing it with the two fixing tabs.
- Fill the mold in three layers, each approximately one-third the height of the mold after clamping. Prick each layer 25 times with the quilting rod. Distribute the strokes evenly over the section of each layer. For the bottom layer, it is necessary to tilt the pin slightly and give approximately half of the stitches with spiral strokes to the center. Prick the second and top layers, each through its entire thickness, so that the rod penetrates slightly into the underlying layer (Figure 8).



Figure 8. Concrete layer pitting in the Abrams cone

When filling and compacting the top layer, put an excess of concrete on top of the mold before starting the pitting. If during the pitting of the top layer a lack of concrete appears below the top edge of the mold. Add more concrete so that there is always an excess. After the top layer has been properly pitted, level the

concrete along the top edge of the mold with a sawing and rolling motion using the pitting rod.

- Remove the concrete that has spilled onto the base plate. Demold the concrete by carefully lifting the mold vertically.
- Immediately after removing the mold, measure the slump (h) by determining the difference between the height of the mold and the highest point of the slumped test specimen (Figure 9).



Figure 9. Slump measurement of concrete with Abrams cone

2.3.2.2 Conservation of cylindrical specimens: The specimens used for determining the compressive strength of the different concretes under test are cylindrical specimens with a diameter of 16 cm and a height of 32 cm (Figure 6). The control concrete and the glass powder concretes were placed in the cylindrical specimens by vibration using traditional vibratory devices (mainly vibrating needle and vibrating table). After casting, the specimens were left at room temperature in the laboratory (Figure 10) and were demolded after 24 hours. After demolding, they were kept in a bath at 20°C for 28 days (Figure 11).



Figure 10. Test specimens before demolding



Figure 11. Samples kept in a bath at 20°C for 28-days

2.4 Hardened concrete

2.4.1 Tests on hardened concrete

2.4.1.1 Uniaxial compression test: The uniaxial compression test concerns cylindrical specimens that have been kept in a bath at 20°C for 28 days. The purpose of the test is to evaluate the compressive strength at 28 days of the different concretes

tested. The hydraulic press used has a maximum capacity of 3000 kN. The compressive strength was evaluated according to the NF EN 12390-3 standard.

The tests were carried out with a loading speed of 0.5 MPa/s. Beforehand, the specimen undergoes a surfacing operation (sand/sulphur mortar in accordance with NF EN 12390-3) (Figure 12).



Figure 12. Surfacing of the specimen with sulfur and sand

The surfacing operation makes it possible to obtain flat surfaces parallel to each other and perpendicular to the generatrices of the specimens, which generates a uniform distribution of the compression force over the entire transverse surface of the cylindrical specimen during the test. It can be controlled using a KN concrete press with a digital acquisition unit. The specimen must meet the visual conformity (crack shape after breaking) and the pressure applied until breaking. Descriptively, the cylindrical specimen, once ground, must be centered on the test press (Figure 13).

The breaking load is the maximum load recorded during the test. The compressive strength is the ratio of the breaking load to the cross section of the specimen (Benboudjema 2002). The maximum load P (MN) and the loading area S (m²) are then noted, the maximum stress (compressive strength) is then written:

$$\sigma_c \text{ (MPa)} = P / S$$



Figure 13. Compression testing

3. PRESENTATION AND INTERPRETATION OF RESULTS

3.1 Fresh state

3.1.1 Slump tests: Tables 10 and 11 show the Abrams-cone slump measurements of the tested concretes in the cases where $W/B=0.5$ and $W/C=0.5$ respectively. Figure 14 shows the variation of the Abrams cone slump of the concretes as a function of the incorporated glass powder percentage and according to the fixed W/B and W/C ratios.

Concrete type	Slump (cm)	Concrete consistency
W/B=0.5		
Control concrete	15	Highly plastic concrete
Concrete with 10% of GP	11	Highly plastic concrete
Concrete with 15% of GP	9	Plastic concrete
Concrete with 20% of GP	8	Plastic concrete

Table 10. Abrams-cone slump of the tested concretes according to the $W/B=0.5$ ratio

Concrete type	Slump (cm)	Concrete consistency
W/C=0.5		
Concrete with 10% of GP	5	Firm concrete
Concrete with 15% of GP	3	Firm concrete
Concrete with 20% of GP	1	Highly firm concrete

Table 11. Cone-slump of the tested concretes according to the W/C=0.5 ratio

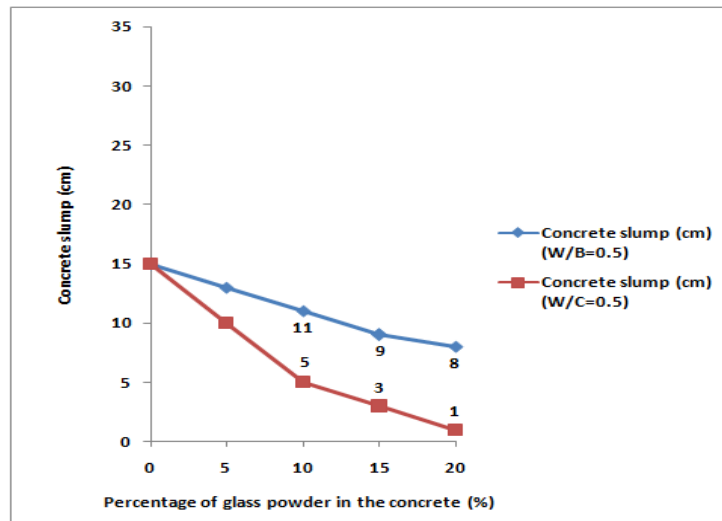


Figure 14. Variation of the slump level according to the incorporated glass powder content and according to the fixed W/B and W/C ratios

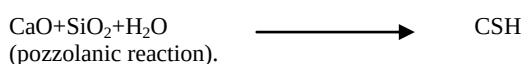
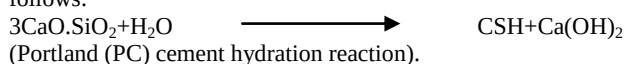
3.1.2 Slump level interpretation with W/B=0.5: The W/B ratio is fixed at 0.5, this indicates two facts:

- The glass powder incorporated is considered as a binder,
- the quantity of water is constant in all the tested concretes.

In figure 14, we notice a decrease of the Abrams cone slump with the increase of the incorporated glass powder percentage. This can be explained by the influence of the glass powder which is characterized by a high demand of water compared to the cement, thus reducing the fluidity of the concrete.

But how can this high water demand be explained? Glass powder is a white alternative cement addition. It is obtained after the collection and grinding of flat glass fragments. Its high content of amorphous silica SiO_2 gives it pozzolanic properties by combining with lime to produce other hydrates (Chekireb 2015). A material is said to be pozzolanic if, in the presence of water, it has the property of combining with lime to form a binder. Most pozzolanic materials contain a form of reactive vitreous silica that, in the presence of water, can combine with the aid of the temperature released by the hydration of C_2S and C_3S in Portland cement, with lime to form a hydrated calcium silicate (C-S-H) similar to that formed during the hydration of Portland cement (Dron and Voinovitch 1982).

The hydraulic and pozzolanic reactions can be described as follows:



We can see that the pozzolanic reaction consumes calcium hydroxide or Portlandite ($\text{Ca}(\text{OH})_2$) to form hydrated calcium silicate (C-S-H). It should be noted that at the ambient temperature, this reaction is generally slow and can develop over several weeks. However, the finer and glassier the pozzolan, the more rapidly it reacts with lime (Papadakis and Vénuat 1966). According to Shao et al (Shao et al. 2000), finer glass ($38 \mu\text{m}$) is more reactive, but its use may increase the water demand depending on its fineness. Indeed, some additions, such as potentially pozzolanic glass, have a high water demand compared to chemically inert limestone filler, which can reduce the workability properties of concrete (Ali Boucetta and Behim 2013).

Figure 15 shows the evolution of the workability of ordinary concrete as a function of the W/C ratio. The general observation is that the slump at the Abrams cone increases with the growth of the W/C ratio (Houria and Nourredine). If we deduce the values of the W/C ratio of the tested concretes, we find the following value in table 12.

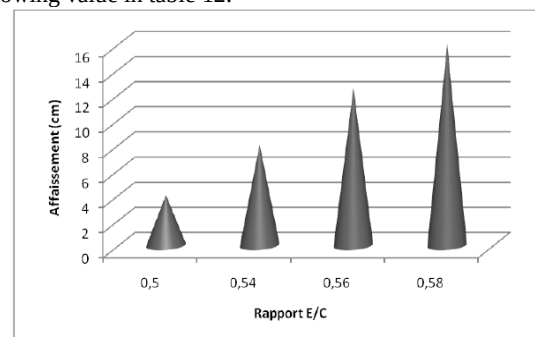


Figure 15. The influence of the W/C ratio on the workability

Concrete type	W/B	W/C
Control concrete	0.5	0.50
Concrete with 10% of GP	0.5	0.56
Concrete with 15% of GP	0.5	0.59
Concrete with 20% of GP	0.5	0.63

Table 12. Values of the W/C ratio of the various tested concretes

Referring to Table 12, the values of the W/C ratio increase progressively, since the quantity of cement will be decreased after each increase of the percentage of glass powder introduced to the concrete, therefore, automatically the slump at the Abrams cone will increase (see Figure 15). However, we notice the decrease of the slump at the Abrams cone? This means that the glass powder has a high demand for water, this high demand increases with the increase of the percentage of glass powder. From the mentioned above, we can conclude that the increase of the percentage of glass powder in concrete with the behavior of very fine GP (fineness similar to that of cement), requires an increasing demand of water, for its strong character of water absorption, on the one hand, and for the pozzolanic reaction on the other hand, and the more the fine glass powder, is more reactive and its use in concrete can increase the demand of water according to its fineness.

3.1.3 Slump level interpretation with W/C=0.5: The W/C ratio is set to 0.5, this indicates two points:

1. The incorporated glass powder is considered as an addition,
2. The amount of water will be decreased with the decrease of the amount of cement.

According to figure 14, we notice a considerable decrease of the slump level with the increase of the percentage of incorporated glass powder. The evolution of the slump level of the tested concretes in this case is lower than that of the concretes prepared with the ratio W/B=0.5. This low slump level of the tested concretes is interpreted, on the one hand, by the influence of the glass powder which is characterized by a high demand of water compared to the cement, as we have seen previously, and on the other hand by the decrease of the quantity of water in the tested concretes with the reduction of the quantity of cement, thus a firm behavior of the concretes based on the cement and glass powder.

Note that: At a percentage of 20% of glass powder, the implementation of the prepared concrete was very complicated, given its very firm behavior.

3.2 Hardened state

3.2.1 Uniaxial compression tests: Tables. 13 and 14 show the compressive strength values of the tested concretes at 28-days in the case where W/B=0.5 and W/C=0.5 respectively.

Concrete type	Compressive strength -28 days (Mpa)
W/B=0.5	
Control concrete	27.20
Concrete with 10% of GP	28.83
Concrete with 15% of GP	29.35
Concrete with 20% of GP	29.87

Table 13. Compressive strength values of tested concrete at 28-days according to the W/B=0.5 ratio

Concrete type	Compressive strength -28 days (Mpa)
W/C=0.5	
Concrete with 10% of GP	31.05
Concrete with 15% of GP	31.62
Concrete with 20% of GP	32.20

Table 14. Compressive strength values of tested concretes at 28-days according to the W/C=0.5 ratio

Figure 16 shows the variation in compressive strength of concrete at 28-days as a function of the percentage of incorporated glass powder and according to the set W/B and W/C ratios.

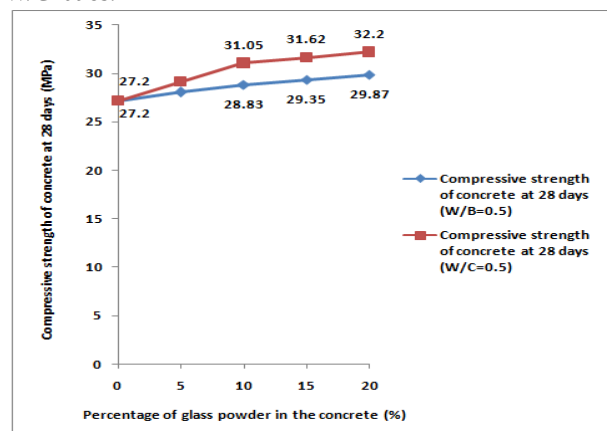


Figure 16. Variation of the compressive strength of concrete at 28-days as a function of the percentage of incorporated glass powder and according to the set W/B and W/C ratios

3.2.2 Interpretation of the uniaxial compression test results for W/B=0.5: According to Figure 16, and in the case where W/B=0.5, we notice a slight increase of the compressive strength of the tested concretes at 28-days with the increasing of the glass powder percentage.

The improvement in strength can be explained by: the physical and chemical effect of the glass powder. The glass powder adjusts the granulometry of the cement (filling), thus increasing the compactness of the paste (physical effect) (Zeghichi, Mezghiche, and Benghazi 2012). It exhibits a pozzolanic reaction with the hydration products of clinker to form dense hydrated calcium silicates (C-S-H) (Chemical effect) (Shi et al. 2005). On the other hand, the hydration of Portland cement releases a large amount of lime as a result of the hydration reaction of C₃S and C₂S (30% of the anhydrous mass of cement). This lime contributes little to the strength of the hydrated cement paste.

When we manufacture concrete, if we use 20% to 30% of pozzolan theoretically, we could react all the lime produced by the hydration of Portland cement to transform into C-S-H. However, the conditions under which concrete is used are very different from this ideal situation and the pozzolanic reaction is never complete (Sargolzhahi 2007). The pozzolanic reaction in concrete develops by consumption of Portlandite (CH) and produces hydrated calcium silicate (C-S-H), which can increase the compressive strength of mortar and concrete (Chan and Chu 2004). Shao et al (2000) (Shao et al. 2000) concluded in their study that the addition of finely ground glass powder leads to an increase in the pozzolanic activity of glass and a progressive

increase in the compressive strength of concrete. The grains of glass powder having the same size as that of Portland cement are well dispersed in the cement paste, which can create a dense structure with microporosity. There is a visible densification around the grains of glass powder due to the partial hydration of these grains which can form the C-S-H phase (Sargolzhahi 2007).

The W/C ratio has a great influence on the compressive strength, when W/C is low the strength increases, a reduction of 15 liters (per m^3) of mixing water leads to an increase of 5 to 10% of the compressive strength (Arnould et al. 1986). Figure 17 shows that the compressive strength of concrete increases as the W/C ratio decreases and as the age of the concrete increases.

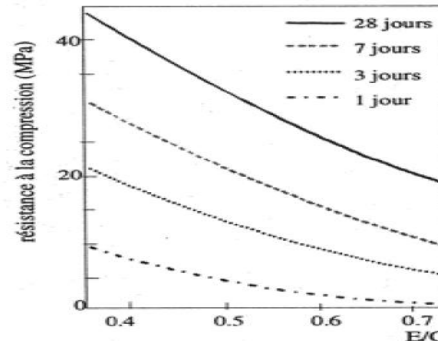


Figure 17. Influence of the W/C ratio on the compressive strength of concrete

Previously, we have deduced the values of the W/C ratio of the tested concrete (see table 12). These values of the W/C ratio increase progressively, since the quantity of cement will be decreased after each increase of the percentage of glass powder introduced to the concrete, therefore, automatically the compressive strength at 28 days will be decreased (see figure 17). However, we notice the increase of this resistance? Therefore, we can say that the added glass powder to the concrete has a very important role in the improvement of the compressive strength of the concrete. Finally, from the above, we can conclude, that the substitution of up to 20% glass powder in concrete, can improve the compressive strength of concrete at 28 days, despite, the high values of the W/C ratio, this improvement is due to the primary role of glass powder in the composition of concrete, by its physical and chemical performance. And with a fineness similar to that of cement, the gain will be supreme. The results show that the compressive strength increases with the increase of the percentage of glass powder in the range of 10% to 25%, beyond this percentage the strength is affected (Zeghichi, Mezghiche, and Benghazi 2012). Researchers have found that beyond 25% or 30% of the glass powder, the compressive strength is affected. This is due to:

- The 20% to 30% of glass powder only needed to react with all the lime produced by the hydration of Portland cement to transform into hydrated calcium silicate (C-S-H). The latter plays a considerable role in increasing the compressive strength of concrete at 28 days and the amount in excess of 30% will be inactive (Sargolzhahi 2007).
- The increase of the percentage of glass powder beyond 30%, leads to the decrease of the quantity of cement, therefore, for a ratio W/B=0.5, that is, high values of W/C, which will decrease the compressive strength of concrete at 28 days. And for ratio W/C=0.5, the quantity of water will decrease with the decrease of the quantity of cement, and we cannot imagine the state of the prepared concrete in the fresh state since at the rate of 20% of the glass powder, we have abruptly a very firm concrete (slump level of 1 cm).

The increase in strength generated by the addition of glass powder by the filling effect and by the pozzolanic effect (thus by the fixation of the Portlandite generated by the hydration of the cement minerals), constitutes a property of durability which

makes it possible to consider the use of glass in the composition of concrete. However, it is necessary to validate the durability of the use of glass powder in concrete by other works.

3.2.3 Interpretation of the uniaxial compression test results

for W/C=0.5: According to Figure 16, and in the case where W/C=0.5, we notice an increase of the compressive strength of the concretes tested at 28 days with the increase of the incorporated glass powder percentage. As we have seen previously, the increase in the compressive strength of the concretes tested at 28 days is justified by the physical and chemical effect of the glass powder. The evolution of the compressive strength of the concretes tested at 28 days in this case is more advantageous than that of the concretes prepared with the ratio W/B=0.5. This improvement in strength can be justified by the decrease in the amount of water in the tested concretes. Therefore, in order to have a good mechanical behavior of the concrete based on cement and glass powder, it is necessary to maintain a ratio W/C=0.5. However, this factor can lead to a firm consistency of the concrete.

4. CONCLUSION

Concrete technology incorporating crushed glass fragments is part of a sustainable development approach. Indeed, this technology allows to participate in the protection of the environment by the recovery of glass waste thrown to nature, which will be crushed and used as an alternative cementitious addition to concrete. In addition, the introduction of glass powder in concrete leads to improve its mechanical properties and reduce the use of cement. Therefore, this technique has an environmental, technological and economic aspect. The main objective assigned to this work was to valorize the addition of glass powder in the composition of concrete and to develop its use as an alternative cement additive through the experimental characterization of the mechanical properties of concrete based on cement and glass powder.

- Experimental test results on fresh concrete showed the effect of glass powder on water demand compared to cement. We have convinced that the increase of the percentage of glass powder in concrete with the behavior of

very fine GP (fineness similar to that of cement), requires an increasing demand of water, for its strong character of water absorption, on the one hand, and for its pozzolanic reaction on the other hand, and the more the fine glass powder, is more reactive and its use in concrete can increase the demand of water according to its fineness.

- For the concretes elaborated with cement and glass powder with the ratio $E/L=0.5$, the glass powder reduced the slump at the Abrams cone compared to the control concrete, but these concretes kept an acceptable plastic consistency. For the concretes elaborated with the ratio $W/C=0.5$, the slump at the Abrams cone became lower following the reduction of the quantity of water in the concrete, thus, a very firm consistency, in particular, with an addition of 20% in glass powder.
- Experimental test results on hardened concrete showed the role of glass powder in improving the compressive strength compared to ordinary concrete (control). The improvement in compressive strength is interpreted by the physical and chemical effect of the glass powder. The physical effect appeared in the adjustment of the granulometry of the cement (filling), thus increasing the compactness of the paste. The chemical effect is on its pozzolanic reaction with the hydration products of the clinker to form dense hydrated calcium silicates (C-S-H) contributing to the increase in compressive strength.
- The evolution of the 28-day compressive strength of concretes prepared with the ratio $W/C=0.5$ is more advantageous than that of concretes prepared with the ratio $W/B=0.5$. This improvement in strength is justified by the decrease in the amount of water in the concretes tested. Therefore, in order to have a good mechanical behavior of the concrete based on cement and glass powder, it is necessary to maintain a ratio $W/C=0.5$. However, this factor can lead to a firm consistency of the concrete.
- We can conclude, that the substitution of up to 20% of glass powder in concrete, has improved the compressive strength of concrete, this improvement is due to the primary role of glass powder in the composition of concrete, by its physical and chemical performance. And with fineness similar to that of cement, the gain will be supreme. The results show that the compressive strength increases with the increase of the percentage of glass powder in the range of 10% to 25%, beyond this percentage the strength is affected.

Finally we have considered the concrete elaborated with 20% glass powder and a ratio $E/L=0.5$ the most advantageous, given its acceptable plastic consistency easy to implement and its improved resistance to compression.

This research project answered the question of the feasibility of introducing glass powder into concrete given its improved mechanical properties. The work carried out can be considered as preliminary, it raises other questions and opens the way to different points to explore, we recommend to:

- Study the effects of GP in different finenesses on the properties of concrete in the fresh and hardened state.
- Expand the testing of cement and glass powder based concretes to structural elements (columns and beams).

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