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Effect of Gravel Content on Mechanical Performance and Porous Structure of Concrete

Abderrachid Amriou[1*], Hocine Ziani[2], Sadek Deboucha[2], Mohamed Bencheikh[1]

[1] Laboratory of Materials and Mechanics of Structure, Faculty of Technology, Civil Engineering Department, Mohamed Boudiaf University, PO Box 166 Ichbilia, M'sila 28000, Algeria
[2] Civil Engineering Department, University of Bordj bou Arreridj, Bordj Bou Arreridj 34030, Algeria

Corresponding Author Email: abderrachid.amriou@univ-msila.dz

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ABSTRACT

Concrete is the most widely used material in the field of civil engineering. In order to obtain a strong and durable concrete, it is necessary to study the various parameters entering into its formulation. Mainly the elements forming the concrete skeleton, in particular the gravel content. The transfer of water into concrete directly affects its durability. This transfer is linked to the porous structure and to the continuity of the pores in the concrete. This research studies the effect of gravel content on compressive strength, porosity accessible to water, depth of water penetration and ultrasonic velocity of concrete samples. The study includes 15 types of concrete made by varying the gravel-sand ratio (G/S), 0, 1, 1.5, 2 and 2.5. The cement dosage is taken equal to 150, 250 and 350 Kg/m^3. The tests are carried out on cubic samples 10x10x10 cm^3 and 15x15x15 cm^3 after storage in water for 28 days. The experimental results obtained show that the gravel-sand ratio (G/S) affects the mechanical strength and the porous structure of concrete. Increasing the gravel content in concrete leads to an increase in mechanical strength and ultrasonic speed. However, a high gravel content results in a reduction in the porosity accessible to water and the depth of water penetration.

1. INTRODUCTION

Concrete must maintain its strength and perform its function for as long as it takes. Concrete is durable if it is able to withstand the deterioration mechanisms to which it may be exposed [1]. The formulation study of a concrete consists in determining the proportions of its various constituents to make an economical, resistant and durable material with a certain workability in the fresh state. During hydration the volume of hydrates increases, the intergranular species initially filled with mixing water is filled and the porosity decreases [2]. Porosity is the first order parameter to consider when studying the strength and durability of concrete. This porosity can be controlled by the water/cement ratio (W/C), the particle size distribution (cement + aggregate), the type of constituent materials and the age of the sample [3, 4]. The permeability of concrete is influenced by the capillary pores. This permeability depends on the size of the pores and their interconnections. It is strongly influenced by the amount of water and the amount of cement [5-7].

Several studies have been carried out on the effect of aggregate volume on the compressive strength of concrete cubes. In these studies, for a given quantity of cement paste different volumes of aggregates as a percentage of the total volume were taken. The results obtained confirm that when the aggregate volume increases from 0 to 20%, there is a decrease in resistance while, between 40 and 80%, this resistance undergoes an increase [8]. The above behavior is verified, whatever the W/C ratio [9]. The influence of the aggregate volume appears clearly in the case of an aggregate concentration of 60 to 75%. In the case of tests carried out on cylindrical samples, the resistance decreases with the increase in the volume of the aggregates from 8 to 40% [10]. It should be noted that the effect of aggregates can be modified by an increase in the entrained air as the workability decreases. In a mixture, the volume of air can play a role similar to that of water for resistance [11]. A study published by Walker and Bloem in the 1960s, this study assumes that for large diameter aggregates (D), concrete, more compact, would exhibit higher mechanical strength and better durability [12]. Another study by Soroka shows that the strength of concrete generally depends on three factors: the strength of the cement paste; and the bond strength between the aggregate and the cement paste. Thus, the effect of aggregate strength on concrete strength depends on the relative strength of the cement paste and the internal bond strength [13].

The size of the aggregates has a significant effect on the behavior of concrete, affecting its economy, workability and strength. For a given water/cement (W/C) ratio, the amount of water used in a mixture is inversely proportional to the maximum size of the aggregates. Thus, the use of larger size aggregates decreases the amount of cement paste needed to bind the particles, which is why concrete mixes with large amounts of coarse aggregate are less easy to work and very difficult to work with. To finish. Conversely, the use of finer particles leads to the use of more cement in order to maintain a constant aggregate / cement ratio, which at the same time decreases the workability of the concrete, while improving its finish [14, 15].

Fresh concrete is said to be achievable if it is easily transported, placed, compacted and finished without any segregation. Workability gives insight into the plastic behavior of fresh concrete. Much research has been done on the factors affecting handling. These factors mainly affect the size, shape and particle size of aggregates, porosity and W/C ratio. According to Marar and Eren, when the cement content increases, the compaction factor increases, but in relation to other constituents like water [16]. The work of Neville and Brooks shows that for given aggregate, cement and water contents, the workability of concrete is influenced by the total surface area of the aggregate. This surface area is governed by the size, grain size and shape of the aggregate [17]. The porosity of an aggregate can affects the workability of concrete, the aggregate absorbing more water, reducing the workability of the mixture [18]. The size of the aggregates influences the specific surface area, a finer aggregate requires more cement paste to effectively wet all of the aggregates thus reducing workability. However, a coarser aggregate will increase workability by providing a smaller surface area available for wetting [19].

In hardened concrete, the higher percentage of aggregates in the concrete mix greatly contributes to its strength [20]. Aggregates are responsible for the unit weight, modulus of elasticity and dimensional stability of concrete, as these properties depend on the physical characteristics (strength and bulk density) of the aggregate [21]. The studies carried out by Vilane and Sabelo on the compressive strength of concrete composed of aggregates of 9.5 mm, 13.2 mm and 19.0 mm. These studies show that the compressive strength of concrete increases with increasing aggregate size [22]. Rozalija and Darwin studied the effect of the type, size and content of aggregates on the strength of concrete. The results of this study indicate that the compressive strength of concrete is little affected by the size of the aggregates [23].

The permeability of concrete is strongly influenced by the porosity of the paste, since it is usually much more permeable than aggregates. This porosity is around 10% of the total volume [24]. Aggregates have a very low porosity than cement paste, the paste-aggregate interface is less dense than the rest of the paste and which creates a larger absorption zone. The increase in the volume of the paste (hence the reduction in the aggregate content) leads to an increase in the absorption of concrete, especially for concretes with a high W/C ratio [25].

Concrete properties can be estimated by ultrasonic pulse velocity measurement methods. These techniques are widely used to quantify the elastic properties of materials, as well as for the detection of cavities and cracks. Several studies have been established to study the sensitivity of the propagation parameters of acoustic waves to the porous structure of concrete. These methods consist in measuring the time taken by a wave to travel through a thickness of a concrete sample [25-27]. According to Leslie and Cheesman, the unknown state of concrete can be roughly determined by determining its measured velocity [28]. Pulse propagation speed measurements can be performed on laboratory specimens or on in situ concrete structures. These measures can be influenced by certain factors [29]:

- Sound waves travel faster through a void filled with water than through a void filled with air. Therefore, the moisture conditions of the concrete influence the measurements taken of the speed of the sound waves,
- The surface on which the test is carried out must perfectly match the shape of the device, it is recommended to use an intermediate material between the concrete and the transducers. Usually, commercial petroleum jelly is used. If the concrete surface is very rough, it is necessary to sand and level this surface,
- An increase in pulse speed occurs at temperatures below freezing due to freezing of the water,
- The presence of steel following the path of the wave in the concrete causes an increase in speed.

In conclusion. For a given composition and a given aggregate, the speed of wave propagation depends on the modifications in the hardened cement paste. The change in the Water/Cement ratio, the cement dosage, the nature of aggregates, the grain size and the humidity of the concrete, can influence the modulus of elasticity.

The aim of this research was to determine the influence of the main constituents that go into the formulation of concrete and that influence its mechanical performance and durability. To achieve this goal, the effect of gravel content was studied. In this context, 15 types of concrete were prepared. These concretes were made by varying the gravel-sand ratio (G / S), 0, 1, 1.5, 2 and 2.5 with three cement dosages 150, 250 and 350 Kg/m^3. The tests were carried out on cubic samples 10x10x10 cm^3 and 15x15x15 cm^3. Compressive strength, water accessible porosity, water penetration depth and ultrasonic velocity tests were performed.

2. EXPERIMENTAL PROGRAM

2.1 Materials and mix compositions

In the present work, the various tests were carried out on 15 types of concrete. These concretes are made from local materials with Portland limestone cement (CEM II / A-L 42.5N). Five gravel-sand ratios (G/S), 0, 1, 1.5, 2 and 2.5 and three dosages of cement (150, 250 and 350 Kg/m^3) were used for the preparation of the different samples of concrete. The fine aggregate used is crushed quarry sand. This sand was passed through a No. 5 sieve before use. Two fractions of gravel (3/8) and (8/16) of limestone origin were used. The quantity of water is determined and corrected to have a concrete (plastic) of a class S3 consistency (subsidence 50 mm to 90 mm). The workability classes are mentioned in the standard EN206: 1990. The desired workability of different types of concrete is verified by the slump test [30]. The mixing was carried out in a small mixer. The placement of the concrete in the molds was carried out in two layers compacted on a vibrating table. After 24 hours of casting, the test pieces were demolded and stored in water at a temperature of 20 ± 2°C until the test age of 28 days.

Table 1. Composition of concrete

№	Sand (Kg)	G 3/8 (Kg)	G 8/16 (Kg)	G/S	CEMENT (Kg)	W/C
1	1830	0	0	0	350	0.95
2	913	264	654	1	350	0.64
3	720	243	842	1,5	350	0.61
4	609	208	1018	2	350	0.57
5	520	201	1101	2,5	350	0.53
6	1916	0	0	0	250	1.35
7	946	281	674	1	250	0.97
8	759	255	887	1,5	250	0.86
9	627	220	1063	2	250	0.79
10	545	214	1149	2,5	250	0.75
11	2006	0	0	0	150	2.40
12	1002	299	703	1	150	1.53
13	795	276	924	1,5	150	1.47
14	665	224	1107	2	150	1.41
15	574	222	1214	2,5	150	1.39

Table 1 summarizes the experimental program of this study. For each type of concrete, twelve specimens were made (six 10x10x10 cm^3 specimens and six 15x15x15 cm^3 Specimens).

2.2 Strength measurements

Compression tests were carried out on three test specimens (10x10x10 cm^3) of each type of concrete (Figure 1). These tests are carried out according to the standard (NF P 18-406): the test consists in subjecting the test specimen under study to an increasing load until fractures. The compressive strength is the ratio of the breaking load to the cross section of the specimen. The charge is carried out at a rate of 0.5 MPa / s [31].

Figure 1. Compression test apparatus

2.3 Determination of porosity accessible to water

The porosity tests accessible to water are carried out according to the standard (NF EN 18-459). The objective of this test is to measure the percentage of void connected to the concrete surface. The principle of the test is based on a series of air and hydrostatic weighing of the samples.

The three samples of each concrete were weighed under water and in the saturated dry surface condition. Each sample was then dried in an oven at a temperature of 105°C. until a constant mass was obtained (the mass does not vary by more than 0.05% between two weighing spaced 24 hours apart). The porosity accessible to water is calculated by the following relation:

$$P = \frac{Ws-Wd}{Ws-Ww} X\ 100\% \quad (1)$$

where, P is the porosity (100%), Ws is the specimen weight in the saturated surface dry (S) condition (g), Wd is the specimen dry weight after 24 h in oven (g), and Ww is the weight of saturated specimens (g).

This method has been used in several studies to determine the porosity accessible to water in cementitious materials [32-34].

2.4 Determination of the depth of water penetration

The water permeability tests were carried out according to European standard A 12390-8: 2009. This method consists of determining the depth of penetration of pressurized water into a specimen of hardened concrete stored in water [35]. Each test was carried out on three cubic specimens (15x15x15 cm^3) for each type of concrete after 28 days of storage in water. The test consists of applying a water pressure of 5 ± 0.5 bars to the surface of the test pieces for a period of 72 hours. After this time, the sample is split into two parts and the depth of water penetration (H) is measured (Figure 3). The experimental set-up used to perform the permeability test is shown in Figure 2.

Figure 2. Apparatus for measuring water permeability (Water penetration depth)

Figure 3. Penetration depth in concrete samples

2.5 Ultrasonic speed measurement

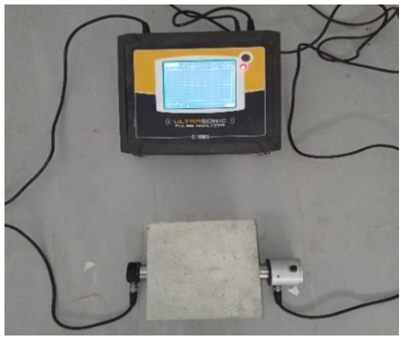

Figure 4. Ultrasonic pulse velocity tester

Ultrasonic Pulse Velocity Test is a method for non-destructive testing of concrete. In this test, longitudinal stress wave pulses are generated by an electroacoustic transducer held in contact with a surface of the concrete to be tested (Figure 4). After passing through the concrete, the pulses are received and converted into energy by a second transducer located at a distance L from the transmitting transducer. The transit time T is measured electronically. Pulse velocity V is calculated by dividing L by T. Measurements were made according to standard (ASTM C597-09) using the pulse velocity ultrasound device [36]. These measurements were carried out on specimens of dimensions 15x15x15 cm^3 (Three samples for each type of concrete). The impulse speed calculated by the following formula:

$$P = \frac{L}{T} \quad (2)$$

where,

V = pulse velocity, m/s,

L = distance between the centers of transducer faces, m,

T = transit time, s.

3. RESULTS AND DISCUSSION

3.1 Relationship between gravel-sand ratio (G/S) and compressive strength

Figures 5 and 6 respectively detect the effect of the gravel-sand ratio (G/S) and gravel content on compressive strength. In Figure 5, we found that the compressive strength increased as a function of the gravel-sand ratio (G/S). For a cement dosage of 350 kg/m^3, this resistance reaches a maximum value of 40 MPa. In the case of cement dosages of 250 kg/m^3 and 150 kg/m^3, the compressive strength reaches its maximum value for a ratio G/S = 2, then a slight decrease in resistance for a ratio G/S = 2.5. By examining Figure 6, it can be seen that the compressive strength is linked to the gravel content in the samples made with a cement dosage of 350 kg/m^3, this resistance increased as a function of the gravel content. For cement dosages of 250 kg/m^3 and 150 kg/m^3, the compressive strength reaches its maximum value for gravel contents of around 50%. Beyond these contents, there is a slight decrease in resistance [37].

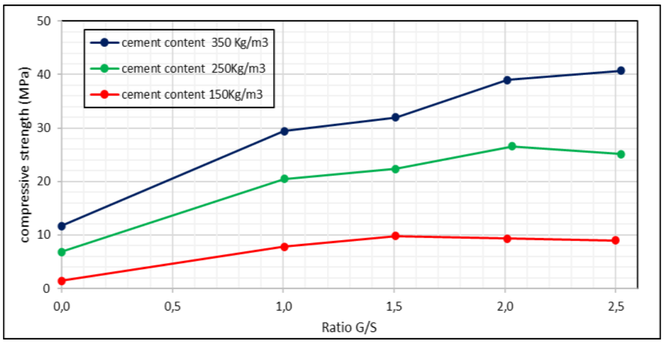

Figure 5. Compressive strength as a function of the Gravel-Sand ratio (G / S)

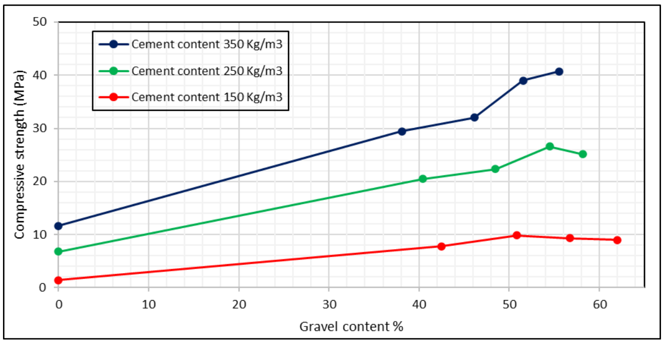

Figure 6. Compressive strength depending on the gravel content

The incorporation of the gravel in the preparation of the samples acts as a skeleton in the concrete, which can improve its compressive strength. However, as mentioned in the previous paragraph, when the gravel content exceeds a maximum limit of about 50%, there is a small decrease in strength. This reduction is due to the lack of cement paste which covers and serves as a binder between the gravel grains, especially in poor cement mixes.

In ordinary concrete, the strength of the aggregate is greater than the strength of the cement paste. The bonding forces between the interfaces of the aggregates and the paste are responsible for the overall compressive strength of the concrete. When cracks form. They are created first in the interracial zone between the aggregate and the paste, then in the cement paste binding the aggregate particles. In the event that these cracks propagate, the concrete will fail. We can therefore conclude that the compressive strength of concrete is related to the cement paste which serves as a bond between the interfaces of the gravel grains [6, 38]. According to Kaplan, the strength of concrete is greater than that of mortar. The incorporation of coarse aggregates leads to the compressive strength of concrete [38].

In Figures 5 and 6, the cement dosage significantly influences the compressive strength. In these figures, we can clearly see the increase in strength depending on the dosage of cement.

According to Gylkey [39]. For workable concrete made under the same mixing conditions, the resistance is influenced by the strength of the mortar, the adhesion between the mortar and the coarse aggregates and the strength of the coarse aggregates (gravel).

3.2 Effect of gravel-sand (G/S) ratio on porosity accessible to water

Figures 7 and 8 show the effect of the gravel-sand ratio (G/S) and the gravel content on the porosity accessible to water of the various concretes studied. From this figure, we first notice that the porosity of concrete decreases as a function of the ratio (G/S) and the gravel content. Secondly, the porosity is influenced by the cement dosage, an increase in the cement dosage leads to a lower porosity.

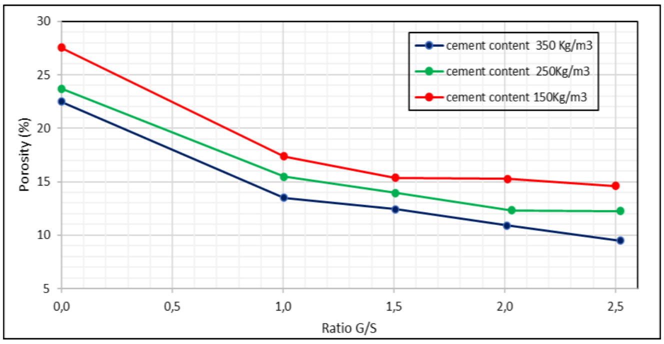

Figure 7. Porosity as a function of the Gravel-Sand ratio (G/S)

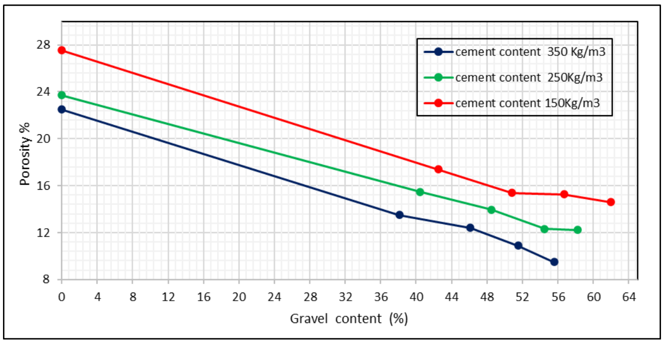

Figure 8. Porosity depending on the gravel content

The porous structure of concrete is formed by hydrate pores and capillary pores. The transfer properties of concretes are strongly influenced by the larger shaped capillary pores in comparison with the hydrate pores. These capillary pores strongly influence the transfer properties of concrete, especially when they are interconnected. To reduce capillary porosity and its interconnection, it is necessary to reduce the W/C ratio and take care of the cure. Since concrete is a composite material comprising a granular phase and a binding phase, its porous structure depends on the granular arrangement and the structuring of the binding phase which is largely a function of the W/C ratio. The penetration of external agents into the concrete is related to the porosity at the exterior surface of the concrete called open porosity and more particularly, to the interconnected open porosity. The percentage of gravel in a concrete mixture influences the amount of water and then the W/C ratio. A high fine grain content requires more water to achieve the workability required. This quantity of water subsequently influences the porosity of the concrete and in particular the interconnected capillary porosity.

Research by Powers et al. [40] explains the influence of the W/C ratio and the degree of hydration on the interconnection of capillaries. According to this research, for W/C ratios greater than 0.7, capillary porosity is always interconnected and transfers in cementitious materials always occur through an interconnected system of capillary pores.

3.3 Effect of gravel-sand (G/S) ratio on the depth of water penetration

Figure 9 illustrates the effect of the gravel-sand ratio (G/S) on the water permeability of concrete measured by the pressurized water penetration test. From this figure, we can make the following remarks:

- The depth of water penetration into the concrete is reduced by increasing the G/S ratio,
- The cement dosage greatly influences the water permeability of concrete. For a cement dosage of 150 kg/m^3, the depth of water penetration reaches double at just six hours compared to the values obtained at 24 hours for concretes dosed 350 kg/m^3 of cement,
- Mortar (without gravel) is more permeable than concrete.

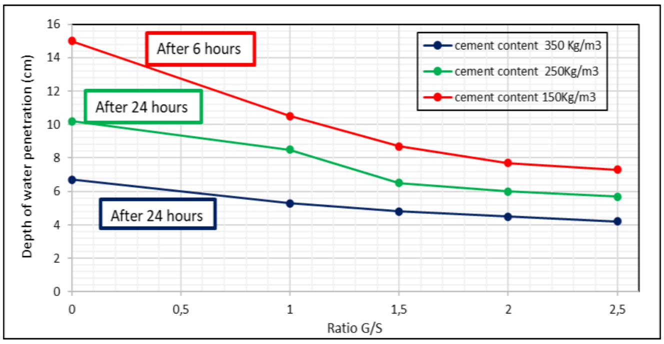

Figure 9. Depth of water penetration as a function of the Gravel-Sand ratio (G/S)

The reduction in the volume of gravel leads to an increase in the volume of paste composed of cement and sand and which requires more water hence the W/C ratio increases. A high volume of pulp leads to an increase in porosity, since it is usually much more permeable than aggregates. According to Larbi's research, the permeability of concrete depends on the internal mass of the cement paste, which is the only continuous phase in concrete. This view is confirmed by the fact that in concrete, water must travel a longer path to bypass the aggregates, which decreases the flow surface and affects the permeability [41].

3.4 Effect of gravel-sand (G/S) ratio on ultrasonic velocity

Figure 10 shows the propagation speed of ultrasonic waves as a function of the gravel-sand ratio (G/S). In this figure, it can be seen that the ultrasonic speed increases as a function of the G/S ratio.

The speed of ultrasonic waves is related to the density of concrete. This ultrasonic speed results from the time taken by the waves to pass through the cement paste and the gravel grains. However, the speed of the waves is related to the dynamic modulus of elasticity of the material under test [6]. Since the modulus of elasticity of gravel in concrete is much higher in comparison with cement paste. So, the modulus of elasticity in concrete is related to the grains of gravel and their quantities. Thus, the ultrasonic speed is a function of the gravel content expressed by the G/S ratio in a concrete.

In Figure 8, we notice that for a fixed G/S ratio, the ultrasonic speed is related to the cement dosage, that is to say to the W/C ratio. Thus, a low dosage of cement resulted in a reduction in the ultrasonic speed. This reduction in speed may be due to the presence of microcracks in the cement paste of these concretes. These microcracks lead to a weaker propagation of waves, and therefore a lower ultrasonic speed.

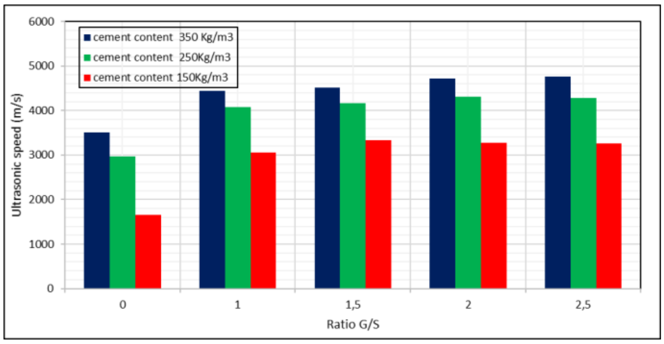

Figure 10. Ultrasonic speed as a function of the Gravel-Sand ratio (G/S)

From the results obtained, the following remarks can be made:

- For each type of concrete in this study, the quantity of mixing water used must make it possible to have a (plastic) concrete with a class S3 consistency. This quantity of water is linked to the percentages of the different constituents of the mixture (sand and gravel). A low ratio mix (G/S) is rich in fine grains, this mix requires more mixing water during mixing. This amount of water affects the properties of hardened concrete (strength, porosity and permeability).

The W/C ratio is the most influential parameter on the capillary porosity volume: for a given cement dosage, the greater the volume of water, the greater the initial space between the cement grains and the greater the capillary porosity is large. This volume of capillary porosity is a determining parameter of the mechanical strength of concrete.

In the case of the cement dosage of 350 kg/m^3, increasing the G/S ratio from 0 to 2.5 contributes to a reduction in the W/C ratio. this reduction of the W/C makes it possible to increase the compressive strength of the concrete.

In the case of dosages of 150 kg/m^3 and 250 kg/m^3, the reduction of the W/C makes it possible to increase the compressive strength of the concrete. The maximum resistance is reached for a ratio G/S = 2.

- Permeability is evaluated by the depth of water penetration in samples (15x15x15) cm^3. This permeability is related to the capillary porosity and mainly the interconnected capillary porosity. This porosity is mainly influenced by the W/C ratio which is linked to the gravel content in the mixtures. If the capillary porosity is interconnected, liquids can penetrate the material, resulting in greater penetration depth.

The cement hydration reaction allows the development of hydrates. The result of this hydration reaction is the formation of a gel called hydrated calcium silicate (C-S-H), crystals of portlandite ($Ca(OH)_2$) and these spaces called capillary pores. This capillary porosity of the paste depends mainly on the W/C ratio. C-S-H make up most of the binder phase of cement paste. C-S-H fibers have the property of bonding to each other and to neighboring crystals. It constitutes the glue of the concrete. Thus, C-S-H are the origin of the mechanical strength of concrete.

For a low G/S ratio, the constituents of the concrete require a greater quantity of mixing water. Excess water can cause interconnected capillary porosity which affects the properties of hardened concrete.

4. CONCLUSIONS

To study the effect of the gravel content on the mechanical performance and the porous structure of concrete, tests on concrete specimens were carried out, the following conclusions were obtained:

1. the compressive strength increases with the gravel-sand ratio (G/S). For a cement dosage of 350 kg/m^3, this resistance reaches a maximum value of 40 MPa for a ratio G/S=2.5. In the case of cement dosages of 250 kg/m^3 and 150 kg/m^3, the compressive strength reaches its maximum value for a ratio G/S=2. This ratio corresponds to a content of about 50% gravel;
2. the porosity accessible to water, the depth of water penetration in the concrete and the ultrasonic speed, decrease by increasing the gravel-sand ratio (G/S);
3. an increase in the cement dosage leads to a lower water-accessible porosity and a high ultrasonic velocity;
4. the cement dosage influences the water permeability of the concrete. For concretes dosed with 150 kg/m^3 of cement, the value of the depth of water penetration during six hours of testing is twice greater than the values obtained for concretes dosed with 350 kg/m^3 of cement for 24 hours. trials. In addition, the depth of water penetration of mortar is greater than that of concrete.

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