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EFFECT OF CONCRETE CLASS, MAXIMUM AGGREGATE SIZE AND SPECIMEN SIZE ON THE COMPRESSIVE STRENGTH OF CORES AND CAST SPECIMENS

ABSTRACT

Core sampling is the most accurate method of evaluating the compressive strength of concrete structures. However, it is preferable to take only small cores to avoid damaging the structures. It turns out that various elements influence the strength of compressed cores. This study examines the influence of specimen size, aggregate size, concrete class, and curing method on compressive strength. Three aggregates measuring 3/8, 8/15, and 15/25 mm are used to make six sets of concrete compositions with strengths of 25 MPa and 30 MPa. Nine specimens are made, one for each variety of aggregate and concrete. Cores of 100 mm, 75 mm, and 50 mm sizes are made. These cores are extracted from concrete blocks curing in the outside air to simulate the real concrete curing environment. Cast specimens cured in water and air with diameters of 50 mm, 100 mm, and 150 mm are also made. The objective is to compare the average compressive strength of all cast or extracted specimens with that of cylindrical standard specimens of diameter 150/300 mm and the cores and cast specimens. The obtained findings showed that the compressive strength is overestimated when we compare f_{p100} cores and standard air-cured specimens (f_c), with a conversion factor varying from 0.69 to 0.96. However, a decrease is observed in comparison with water-cured specimens. The use of f_{p75} cores reduced the conversion factors, which are between 0.83 and 0.87 for B25 concrete. The highest f_p/f_c ratios are obtained for f_{c50} cores, which can reach 1.24. It turns out that the size of the core and the class of concrete have a much greater influence on the f_p/f_c ratios.

Keywords: *Concrete; compressive strength; cast specimens; cores; aggregate size; specimen size*

INTRODUCTION

In Algeria, many construction projects have already been completed, and others are underway. For various reasons, these projects require frequent evaluation of their strength [1]. For concrete, performance assessment is generally related to simple compression measurements [2, 3]. Civil engineers prefer to use conventional non-destructive techniques to determine the compressive strength to preserve structural integrity. However, small cores can be used because this method is the most accurate for determining the compressive strength of concrete in situ and does not compromise the strength already in question.

In most cases, strength measurements are made using conventional forms under ideal conditions. Unfortunately, the use of different-sized forms does not provide concrete with the same strength as the use of standard forms. For this reason, researchers have been forced to

find transitions between specimens of different sizes and shapes [4]. However, this approach should be used with caution, following the guidelines of the current standards [5-9]. In addition, the compressive strength of cores is affected by many factors such as core size, length-to-diameter (L/D) ratio, moisture status, the direction of coring, the moisture of the cores at the time of testing, preparation of the samples, and the corer used, which can cause damage to the cores [10, 11]. The effect of size is demonstrated by a decrease in average fracture stress with increasing specimen volume [12]. As a result, the specimen's size has a significant impact on how compressive strength values are evaluated.

The American standard ASTM C42 recommends a 95 mm size [5]. In contrast, the new European standard EN 13791:2007 specifies a minimum size of 100 mm, which means that the core size should be at least three times the maximum aggregate size [6]. However, the use of small cores smaller than 100 mm is not excluded by increasing the number of cores. In this regard, the question of how many cores should be considered adequate to maximise the efficiency of the compressive strength evaluation process has been raised, especially when using small cores [13, 14]. Indeed, the low number of cores may give a non-representative evaluation of the real strength of the existing structure. Moreover, with the small dimensions of the cores, a very important dispersion of the results can be obtained. Therefore, the conversion of compressive strengths of specimens with standard shapes and dimensions may be difficult [4]. However, to increase the credibility of the results, the use of very large numbers of microcores is often recommended.

A recent study that combines destructive (coring) and non-destructive (NDT) testing to verify concrete quality recommends nine cores [15]. For special cases, these standards allow the use of cores with a size smaller than 50 mm [7-9]. Indeed, an interesting study highlighting the potential of using 44 mm micro-cores in the presence of 10 or 20 mm aggregates was published a few years ago [16]. Other studies have used 30 mm diameter microcores in concrete with the same maximum aggregate size [17, 18]. The study conducted by Indelicato used microcores of smaller sizes (28 mm) [4]. According to his results, the compressive strength of a cube of concrete with a maximum aggregate size of 30 mm can be measured using micro-cores. Except that the strength of these cores is affected by the maximum aggregate size [19, 20]. These tests are considered non-destructive since the damage to the structure is almost always minor. However, in the case of large-sized cores, this causes greater damage to the structure.

The influence of specimen size on the quasi-static and dynamic behaviour of concrete under compression was also demonstrated using a numerical model [21-24]. The findings demonstrate that the failure process is consistent with the concrete material. However, the dynamic impact of size on concrete's compressive strength is still unclear and needs more research. The existence of the size effect was confirmed by Wang et al. [25], as the dynamic compressive strength of concrete cylinders decreases with size. On the other hand, Li et al. study [26] discovered that the size of the cylinder did not affect the dynamic compressive strength of concrete. Recently, Zhangyu et al. [27] attempted to investigate the quasi-static and dynamic behaviour of concrete in compression using a 3D mesoscale modelling approach. The cylinders utilised ranged in size from 50 mm to 200 mm, having an L/D ratio of 1/2. Significant influences on the pattern and failure process came from the strain rate and specimen size, and concrete's quasi-static compressive strength gradually declines as specimen volume changes. However, the dynamic compressive strength of concrete tends to increase as specimen volume increases.

This study presents the results of a large campaign of simple compression tests performed on our sites using cast specimens and cores of various sizes and maximum diameters. However, their transposition to standard 150/300 mm specimens depends on several factors.

For this purpose, the compressive strength values of 324 cast cylindrical specimens are compared with the compressive strength values of 162 cores of 50, 75, and 100 mm in size, extracted from blocks made with the same mixes. Although the effect of specimen size and aggregate size on compressive strength has been extensively studied, the compressive strength of the cores compared to cast specimens stored in water and external air has not been sufficiently explored. Include formulas that relate specimen size, aggregate size, and storage mode to simple compressive strengths. Converting the compressive strength of the cores from our construction sites into standard cylinder strengths could be of great use to designers and contractors.

EXPERIMENTAL

Cement

The cement used is a compound cement of type CEM II/A of class 42.5 MPa whose chemical and mechanical properties are presented in Tables 1 and 2, respectively.

Table 1. *Chemical properties of the used cement (%)*

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	CaO free	Insoluble	Loss on ignition
20.19	5.23	3.34	56.90	2.01	0.61	0.15	2.31	1.01	2.41	5.84

Table 2*. Mechanical properties of cement*

Time (days)	Flexural strength (MPa)	Compressive strength (MPa)
2	4.20 ± 0.04	23.22 ± 0.06
7	7.26 ± 0.05	38.90 ± 0.06
28	8.47 ± 0.06	45.78 ± 0.06

Aggregates used

The concrete is made with materials commonly used on our construction sites. Aggregates of maximum sizes of 8, 15, and 25 mm and sand of a maximum size of 3 mm were used in the elaboration of the concrete. Table 3 presents a summary of the results of the various analyses of the physical characteristics of the different aggregates. Figure 1 shows the particle size distribution of the used sand and aggregate.

Table 3. *Physical characteristics of aggregates*

Caractéristiques	Sand	Gravel		
Granular class	0/3.15	3/8	8/15	15/25
Apparent density (Kg/m^3)	1480	1500	1500	1520
Absolute density (Kg/m^3)	2520	2500	2640	2690
Thinness module	2.11	-	-	-
Sand equivalent (%)	82	-	-	-
Cleanliness of gravel (%)	-	1.4	1.2	0.8

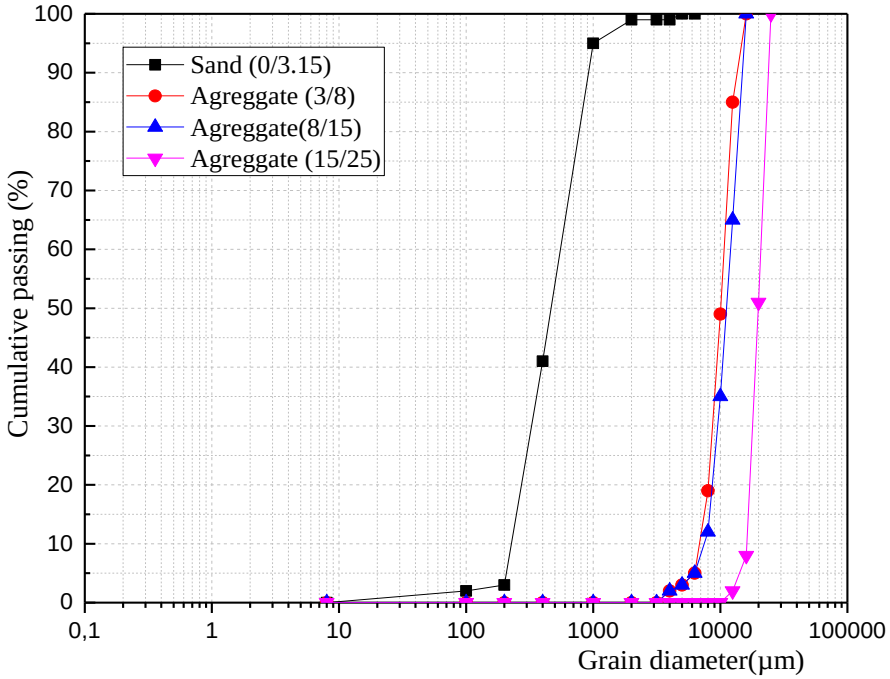


Fig. 1. Grain size distribution of sand and aggregates

Studied mixtures

The concretes studied belong to two families of different strengths; ordinary concrete of 25 MPa (B25) and concrete of 30 MPa (B30). Nine specimens were made for each type of concrete and each type of aggregate. The determination of the composition was carried out by the Dreux-Gorisse method. Table 4 shows the different formulations that were selected for this experimental study.

Table 4. *The studied mixtures*

Tests	Type of concrete	Sand (Kg/m^3)	Gravel (Kg/m^3)			Cement (Kg/m^3)	Water (l/m^3)
		0/3	3/8	8/15	15/25		
1	B25/D8	670	1066	-	-	348	222
2	B30/D8	610	1075	-	-	396	222
3	B25/D15	575	178	1097	-	336	208
4	B30/D15	544	175	1107	-	381	208
5	B25/D25	546	163	421	753	325	200
6	B30/D25	518	142	413	776	367	199

Test procedures

We made the concrete with the help of cast cylindrical specimens and extracted cores from the concrete blocks (Figure 2). Indeed, moulds with cross-sectional dimensions of 50 mm, 100 mm, and 150 mm were used. On the other hand, the cores had dimensions of 50 mm, 75 mm, and 100 mm and were extracted perpendicular to the concrete surface, i.e., in the direction of the concrete. The sampling, conditioning, and preparation procedures were carried out according to ASTM C42 and the European standard EN 12504-1 [5, 6]. To ensure proper curing of the concrete, all cores were taken with a diamond core drill from blocks away from the edges at 23 days post-casting. The collected specimens were stored in airtight containers for five days to reduce the impact of the hydraulic gradient [5]. The

length/diameter (L/D) ratio of all specimens studied is 2. We considered two modes of curing: water for the cast specimens and external air for the cores, to account for the effect of the existing in situ preservation conditions on the structure. At 28 days of age, all specimens were crushed under simple compression using a compression testing machine.

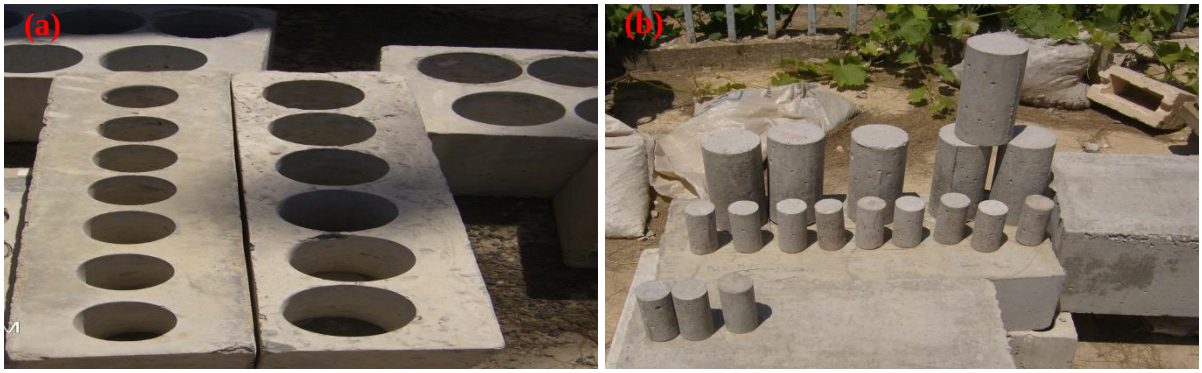


Fig. 2. Tested concretes a) Core drilling operation carried out on the blocks, b) Different specimens cast

ANALYSIS OF THE RESULTS

We evaluated the compressive strength responses of cast specimens that had been made with three different granular sizes and stored in air and water, respectively. Figures 3 and 4 show the average compressive strength values f_c, $f_{c100,}$ and f_{c50} obtained on 9 specimens, where f_c represents the compressive strength of standard specimens at 28 days. These specimens were chosen because they are the most common sizes on our sites. When comparing the compressive strength of the small specimens to that of the large specimens, the results are much more dispersed. For a comparison of the average strength values in the three types of concrete, it is observed that the increase in the aggregate size, in the case of 50 mm cylinders, disturbs the compressive strength. A progressive decrease in the strength of the specimens made with 15 mm and 25 mm aggregates is recorded. The compacting of the concrete is not perfect and the large aggregates are badly distributed. This is called the “wall effect”. To reduce this phenomenon, the standards recommend that the size of the specimen should be greater than three times the size of the aggregate. The British standard BS 1881/part: 110/1983 allows the use of aggregates of 20 mm maximum for cylinders of 100/200 mm [28]. Indeed, the influence of the size of the aggregates starts to disappear from 100 mm. To reduce this phenomenon, the standards recommend that the size of the specimen be greater than three times the aggregate size. The same observation is made for specimens curing in the air (Fig. 4). It should be noted that the compressive strength is lower for air curing than for water curing.

Due to the difficult cohesion of these aggregates, the same tendency but less importance can be obtained by raising the concrete class (B30). Therefore, the compressive strength of small sizes is also affected by the concrete class. However, as the aggregate size increases, the compressive strength of f_{c100} and f_c specimens also increases. In general, we find that the average f_{c100} strength values, especially for specimens cured in air, are slightly higher than those for standard cylindrical specimens.

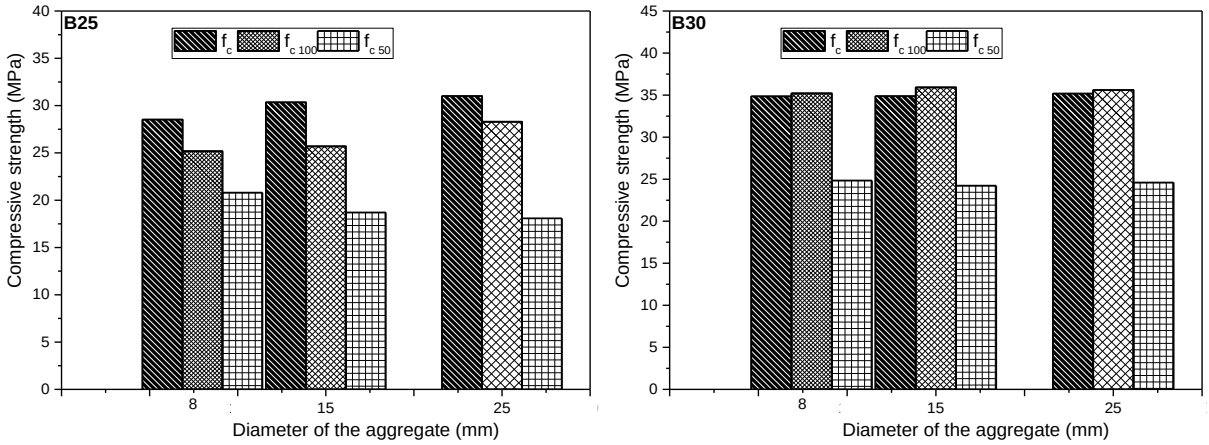


Fig. 3. Evolution of compressive strength as a function of the maximum aggregate size of cast specimens cured in water

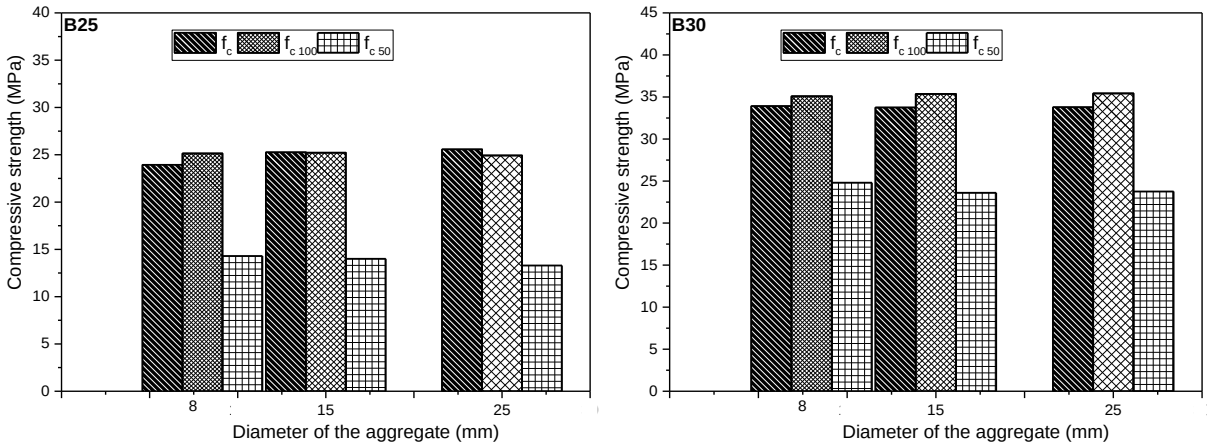


Fig. 4. Evolution of compressive strength as a function of the maximum aggregate size of cast specimens cured in air

The ratios of the different cast specimens to the standard specimen in the two modes of curing are presented in Table 5. The results show that the average compressive strength of the standard specimens of different compositions cured in air decreases by about 0.83 to 0.97 of the strength obtained compared to the specimens cured in water. However, the current standards give a ratio of 0.85 [5, 6, 11]. This ratio is 0.98 to 1 for 100 mm specimens and 0.69 to 1 for 50 mm specimens. These ratios increase specifically when using B30 concrete and decrease when using smaller-size specimens. There is a slight predominance of ratios where $f_{c100}/f_c > 1$. Indeed, this ratio is less than 1 for specimens cured in water, although for class B30, it is significantly higher. However, this ratio is generally slightly higher than 1 for the two classes of concrete cured in the air. This shows unequivocally that the average compressive strength of the 100 mm specimens is close to that of the standard specimens of 150/300 mm.

Table 5. *The ratio of different cast specimens to standard specimens cured in water and air*

Class of concrete	D_{max} (mm)	Cured in water		Cured in the air		Air/Water		
		f_{c100}/f_c	f_{c50}/f_c	f_{c100}/f_c	f_{c50}/f_c	f_c/f_c	f_{c100}/f_{c100}	f_{c50}/f_{c50}
B25	8	0.88	0.73	1.05	0.60	0.84	1.00	0.69
B30	8	1.03	0.70	1,04	0.73	0.97	1.00	1.00
B25	15	0.85	0.62	1.00	0.56	0.83	0.98	0.75
B30	15	1.03	0.70	1.05	0.70	0.97	0.98	0. 97
B25	25	0.91	0.58	0.98	0.52	0.83	0.98	0.74
B30	25	1.01	0.70	1.05	0.70	0.96	1.00	0.97

Figure 5 shows the evolution of the compressive strength of the cores for the two classes of concrete as a function of the maximum aggregate size. It should be remembered that each point in this figure represents 9 measurements. We find that increasing the maximum aggregate size does not affect the f_{p75} and f_{p100} cores. The average compressive strength values have increased, which is a positive result. The compressive strengths of B25 concrete are generally higher than those of the cured standard specimens in both modes studied. This indicates that especially compared to the specimens cured in air, these two cores overestimate the compressive strength. However, we note that the compressive strength of the f_{p50} cores is affected by increasing the maximum aggregate size. As an illustration, for the D25 aggregate, there is a 14% reduction compared to standard specimens cured outdoors a 29% reduction compared to standard specimens cured in water. This is because the bond of the aggregate to the cement paste during coring weakens as the size increases. This has been demonstrated by the work of Bungey [16]. Similar to what was observed with the cast specimens; the results of the core compression evaluation are dispersed with decreasing core size. On the other hand, analysis of the average compressive strength values of the B30 concrete cores reveals broadly the same trends, except for the f_{c75} cores. A close examination of the results in Figure 5 shows that the compressive strength of the f_{c75} cores is lower than that of the standard specimens cured outdoors. This decrease can be explained by the coring operation. It is found that the diameter of the aggregates does not have a negative effect, as the compressive strength changes continuously as the maximum aggregate size increases. It is found that using the D8 size aggregate results in a 14% reduction in compressive strength, compared to only 6% for the D25 size.

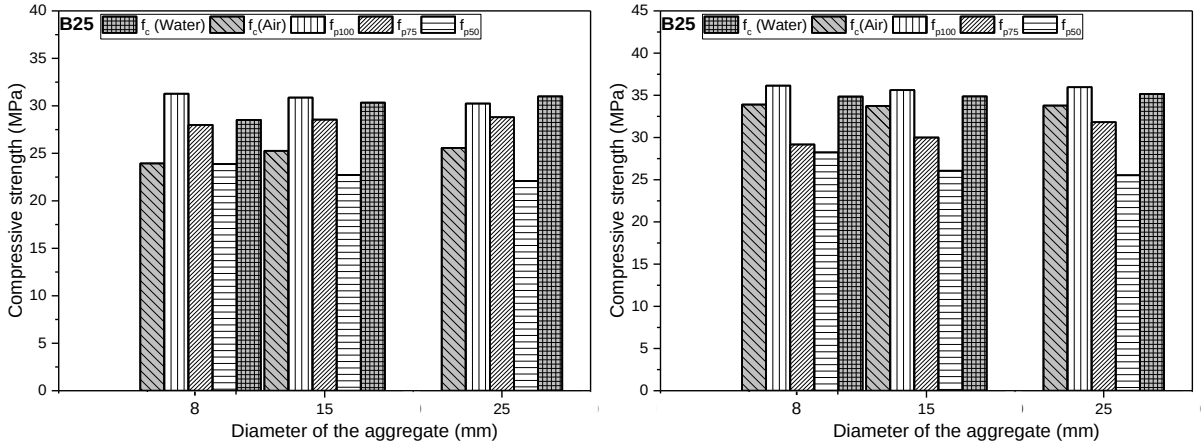


Fig. 5. Compressive strength of cores as a function of maximum aggregate size: Comparison with concrete cured in water and air

The results in Table 6 are based on an analysis of all the data obtained from the crushing tests carried out on cast specimens and cores extracted from concrete blocks. It was considered necessary to analyse all the different sizes to produce conversion factors that could be used immediately on our sites. We compared the average compressive strength values of standard specimens cured in water and air with those of the cast specimens and cores. In addition, we compared the f_c cast specimens and the f_p cores.

The f_p/f_c ratio of compressive strengths is a function of core size D. Similar findings are reported by Seong-Tae et al. [10]. In addition to the effect of size, the type of concrete has also an impact on the f_p/f_c ratio. The B25 class of concrete produces $f_{P100}/f_c > 1$ ratios where f_c is standard specimens cured in air. However, the f_{p75}/f_c ratios of B30 concrete have resulted in a decrease in these ratios.

The $f_{P50}/f_c \leq 1$ ratio for the two curing modes. The conversion factor varies from 1.16 to 1.29 compared to the standard specimens cured in water. We found that this factor varies from 1 to 1.24 when compared to specimens cured in air. The effects of maximum aggregate size are more pronounced with the f_{p50} cores. Examination of these ratios shows unequivocally that they decrease with increasing aggregate size. This finding is proportional to those found by Wang et al. [25]. This is probably due to the disturbance of the concrete during extraction. The cited above standards [5, 7] allow for the use of f_{p50} cores provided that the aggregate size is at least three times the core diameter. Alternatively, it is constrained by the maximum aggregate size. However, the proposed conversion factor values can be used to estimate the compressive strength of f_{p50} cores.

The water curing mode decreases both f_{p100}/f_c and f_{p75}/f_c ratios. However, the f_{p100}/f_c ratios remain close to or above 1, but we observed that the f_{p75}/f_c ratios decrease significantly in this curing mode, which requires conversion factors that range between 1.02 and 1.16 based on the concrete class and the maximum aggregate size used. Based on the above results, we found that core size and concrete class are the dominant factors of compressive strength. Therefore, the conversion factors are influenced by the concrete class and core size.

When the strengths of cast specimens and cores of the same size are compared, the f_p/f_c ratios are greater than 1. This is especially critical when casting concrete in small specimens. Concrete compaction diminishes as the maximum aggregate size increases. The loss in compressive strength of the cast specimens is due to inadequate compaction. Externally hardened cores of size f_{p50} generate higher conversion factors ranging from 0.33 to 0.93.

Table 6. *The ratio between the different experimental results*

Class of concrete	D_{max} (mm)	Cured in water					Cured in the air				
		f_{p100}/f_c	f_{p75}/f_c	f_{p50}/f_c	f_{p100}/f_{c100}	f_{p50}/f_{c50}	f_{p100}/f_c	f_{p75}/f_c	f_{p50}/f_c	f_{p100}/f_{c100}	f_{p50}/f_{c50}
B25	8	1.10	0.98	0.84	1.24	1.15	1.31	1.17	1.00	1.24	1.67
B30	8	1.28	0.84	0.81	1.03	1.14	1.07	0.86	0.83	1.03	1.14
B25	15	1.02	0.94	0.75	1.20	1.21	1.22	1.13	0.90	1.22	1.62
B30	15	1.37	0.86	0.75	0.99	1.08	1.06	0.89	0.77	1.01	1.10
B25	25	0.98	0.93	0.71	1.07	1.22	1.18	1.13	0.86	1.21	1.66
B30	25	1.41	0.90	0.73	1.01	1.04	1.06	0.94	0.76	1.02	1.07

The larger amount of data collected by examining the three different types of concrete in the same class increased the R^2 coefficient value. This increase indicates a considerably stronger linear relationship between f_p and f_c.

To simplify the accurate evaluation of the compressive strength of the f_{p50} cores, all concrete with different granular combinations was grouped. Relationships 1 and 2 are obtained on B25 and B30 concrete and the coefficients (R^2) are 0.97 and 0.84, respectively. Given the larger amount of data available, the results allowed us to obtain very satisfactory coefficients (R^2).

$$f_c = 48.58 - 1.03 f_{p50} \quad (1)$$

$$f_c = 32.30 + 0.06 f_{p50} \quad (2)$$

f_c: Compressive strength of air-cured standard specimens.

The best estimate of f_c based on f_{p50} is provided by equation 1, and given the greater amount of data available, it reflects a satisfactory result.

CONCLUSIONS

The present study investigated the effect of a concrete class, maximum aggregate size, specimen size and curing mode on the compressive strength. The analysis of the experimental data led to the following conclusions:

- The aggregate size and curing method have a significant impact on compressive strength values. However, the type of concrete and the size of the cores are critical, especially for small specimens.
- The ratios of f_{c100} cast specimens to fc standard specimens are often close to 1, moreover, higher than 1 (1.05), particularly in the air-cured mode. However, curing in water has a positive effect on the f_{c100}/f_c ratio (1.03) for concrete class B30 but less than 1 in the case of B25 concrete (0.85).
- The f_{c50} specimens require conversion, which is particularly significant for the B25 concrete class. The conversion factors are high, it is 1.48 for air-cured specimens and 1.42 for water-cured specimens. We found dispersed results with this type of specimen. In addition, we found that the compressive strength decreased with increasing aggregate size.
- For the cores, similar results were obtained for the f_p/f_c ratios, but with larger values. The effect of concrete class on the compressive strength of the cores decreases as the sample size increases. Specifically, the difference in compressive strength between cores and standard specimens begins to fade for f_{p75} cores. This phenomenon is more visible in the case of air curing. The lowest f_{p75}/f_c ratio is recorded for B30 concrete with aggregate size D8 (0.86).
- The f_{p100} cores showed higher f_{p100}/f_c ratios, with values higher than 1 for most of them. In addition, comparisons with standard specimens showed different ratios depending on aggregate size, concrete class, and curing method.
- Compared to standard specimens, the compressive strength of f_{p50} cores is underestimated. Particle size also has an impact on compressive strength, but as the concrete class increases, the result is different. Indeed, the f_{p50}/f_c ratio decreases with the B30 class. We found a reduction in f_{p50} cores of up to 17% for B30 concrete obtained with D8 aggregates and a reduction of almost 24% for the same concrete obtained with D25 aggregate size.

- Simple mathematical formulae are proposed by combining the different aggregate sizes due to the lack of information on concrete, especially for older buildings. The association between the compressive strength of f_{p50} cores and standard specimens is linear. The coefficients found are very high. This allows us to assess the strength of concrete in situ with a high degree of certainty for experienced materials.

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