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In Situ Strength vs. Potential Strength of Concrete: Proposal of a New Procedure for the Assessment of Excess Voidage

Raffaele Pucinotti

Department Heritage, Architecture, Urbanism, Mediterranean University of Reggio Calabria, Via dell'università, 24, 89124 Reggio Calabria, Italy; raffaele.pucinotti@unirc.it; Tel.: +39-0965-1696412

Abstract: Concrete cores extracted from the same structural element may show variations in strength resulting from a lack of homogeneity and variations in the grade of compactness. This paper, while accounting for such variability, introduces a new formulation to assess both in situ and the potential characteristic strength of concrete. The first part addresses the Concrete Society report 11 on formulations and the formulation introduced by the author that considers new coefficients that take into account the addition of water to the cement mixer and the influence of excess voidage. The second part describes a case study in that the procedures were applied to an experimental campaign carried out on two series of cores. The visual means method proposed by report 11 is applied for excess voidage assessment to the first series of cores, while a computed axial tomography (CAT) scan allowing a direct estimate of the percentage of voids in different sections is applied to the cores of the second series. Results show noticeable variations in the percentage of voids within the same drilling. Moreover, the proposed formulation can estimate the actual value of both the in situ and potential characteristic strengths of concrete with a reasonable degree of approximation. Finally, a computed axial tomography (CAT) scan leads to extremely precise results, making it possible to evaluate the percentage of voids in different sections of the same core.

Keywords: concrete; compressive strength; drilling; cores; existing buildings; presence of voids; variations in compaction; Computed Axial Tomography scan (CAT scan)

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1. Introduction

The assessment of the mechanical properties of concrete in situ is a topic addressed by many researchers; consequently, there are many formulations provided by standards [1–7] and proposed in the scientific literature [8–10].

Some of these formulations were extensively reported in [11], where the authors, after clarifying the difference between in situ strength and the potential strength of concrete, compare the results by applying different expressions, highlighting the various factors affecting the estimate of the actual strength. Furthermore, by using different approximations within their validation range, they can give an estimate of the in situ compressive strength of concrete.

However, it is important to remember that among the previous formulations proposed by standards, that is, report 11 [1,3], an estimation of the potential strength of concrete is possible.

In [12], it was shown that, within the same drilling, there are noticeable variations in compaction (presence of voids) and consequently in the compressive strength of concrete. In fact, the presence of voids, effectively allowing us to define the degree of compaction of the concrete in situ, influences the reduction of resistance of the concrete due to poor quality of compaction.

The compressive strength of concrete in an existing structure is conditioned by various factors that are difficult to quantify, especially when dealing with poor-quality concrete [13–16].

Therefore, these anomalies bring about not only a lack of homogeneity and variations in the grade of compactness and resistance in different sections of a structural element but can also cause variations in the resistance even within the same section. The most critical aspect of the strength assessment of concrete is therefore the choice of which points to measure and extract cores from. It is very important to extract (with adequate accuracy) cores representative of the concrete subjected to valuation.

Statistical studies conducted in [11,17] and in [18] confirm the extreme variability of the concrete compressive strength in the same structure. These studies show coefficients of variation (Cv) greater than 0.14. In many cases, the Cv reached 0.35, and in some cases, even 0.50.

All this creates strong doubts about the representativeness of the results of the tests conducted on cores; the cores are generally extracted from one point on a structure, and then the test results are extended to the entire structure. Subsequently, the results are considered valid for the entire single concrete casting structure.

Moreover, all these anomalies, in addition to determining inhomogeneity and variations in the degree of compactness, lead to an incorrect assessment of the potential strength of concrete. This represents a criticality; it is therefore necessary to take cores that are representative of the in situ concrete.

In the absence of available data on the concrete casting, a visual evaluation of the compactness of the concrete can be made to estimate the percentage of excess voids in the test specimen with respect to the photos shown in report 11 [1,3].

In these cases, British standards [3] provide the following classes:

(i) Class 1—void absent, presence of spaces measuring less than 0.5 mm;
(ii) Class 2—small void, a void measuring not less than 0.5 mm and not more than 3 mm across in any direction;
(iii) Class 3—medium void, a void having a dimension greater than 3 mm but not greater than 6 mm;
(iv) Class 4—large void, a void having a dimension greater than 6 mm;
(v) Class 5—honeycombing, interconnected voids arising from, for example, inadequate compaction or a lack of mortar.

In the field of geology, X-ray computed tomography is used to determine the porosity of rock from a single computed tomography, showing that there is an uncertainty in the porosity measurement [19–26].

A new method, called the gray level method, was developed in [27] and considers the computed tomography image as a surface; consequently, the volumes required in porosity estimation are obtained by means of integrating this surface with simple operations applied to the image histogram.

It appears that insufficient research was conducted with reference to the variability of concrete strength within the same drilling or core; no researcher has proposed an alternative method (to that proposed by report 11 [1] and British standards [3]) on the estimate of the percentage of voids in an in situ concrete.

In this paper, a new methodology is introduced that is able to estimate the porosity of in situ concrete and consequently the percentage of voids using a computed axial tomography scan (CAT scan) [28]; this is different from an X-ray machine, which sends just one radiation beam. In fact, the CAT scan produces a more detailed final picture than an X-ray image; it is therefore more performant in the assessment of porosity.

The study shows that the variation in strength is very high and occurs in specimens extracted from the same perforation. This is mainly attributable to the percentage change in voids in the concrete. The percentage change in voids can be estimated by the computed axial tomography scan (CAT) scan in all desired sections of a core.

In fact, generally, in the case of poor quality of the in situ concrete, the responsibilities can be attributed to: (i) the supplier of the concrete, when the acceptance testing of hardened concrete, is not satisfied, while the checks carried out on the extracted cores provide results in line with the acceptance testing; (ii) the construction company, when the acceptance testing of hardened concrete are satisfied and instead the tests carried out on the cores show lower results than expected; (iii) both, the supplier of the concrete and the construction company, when the acceptance testing is not satisfied and also the checks performed on the extracted cores provide lower results than those expected by drilling [23].

It is therefore evident that in the case of poor-quality in situ concrete, when acceptance testing of hardened concrete is not available or when responsibilities are traced (between the concrete supplier and construction company), it is necessary to be able to estimate the actual (in situ) strength of the concrete as well as the potential strength of the concrete.

The remainder of the paper is presented as follows: Initially, Section 2 describes the in situ concrete strength assessment from the formulation proposed by the Concrete Society (report 11), and a new formulation proposed by the author is introduced. In Section 3, the formulation of report 11 is applied to the potential strength assessment; then, a new formulation containing a series of correction coefficients, not considered in [13], is introduced; the correction coefficients take into account, among other things, the addition of water to the cement mixer and the influence of excess voidage.

An experimental campaign carried out on two series of cores is presented in Section 4. In the first series, the visual means method proposed by report 11 is applied to the excess voidage assessment; then the two formulations are applied, and the results are compared. For the specimens of the second series, the excess voidage is assessed using a computed axial tomography (CAT) scan, allowing a direct estimate of the percentage of voids in different sections of the cores.

Finally, the main conclusions are drawn in Section 5.

2. In Situ Strength Assessment

As specified in Section 1, there are many formulations provided by codes [1–6] and proposed in the scientific literature [8–10,16] that assess the mechanical properties of concrete.

This paper only comments on the formulation proposed by the Concrete Society Technical Report 11 and a new formulation proposed by the author in [13] and subsequently augmented by the introduction of new corrective coefficients.

2.1. Concrete Society Technical Report 11

The Concrete Society Technical Report 11 [1] proposes an expression to estimate the actual strength of concrete when taking corrections into account:

$$R_{c,a} = f_{core}\frac{D}{1.5 + 1/\lambda} \tag{1}$$

where

- $R_{c,a}$ is the estimated actual strength;
- D is a parameter depending on the direction of perforation (D = 2.5 for the core drilled in a horizontal direction, and D = 2.3 for the core drilled in a vertical direction);
- λ is the core slenderness (ratio between length and diameter);
- f_{core} is the core strength.

2.2. Pucinotti Method

In [13], an analytical and alternative formulation was proposed in order to estimate the in situ characteristic concrete compressive strength based on a series of destructive laboratory tests on 359 cores. In this paper, the analytic expression is updated with the addition of new coefficients in order to consider the following aspects: (i) the presence of reinforcing bars in the cores; (ii) the moisture condition of the core; (iii) the age of the concrete at the time of the coring.

Therefore, the average value of the in situ compressive strength is calculated by the following equation:

$$f_{cm,a,P} = \left(\sum_{i=1}^{n} \alpha_2^i \cdot C_{dia}^i \cdot C_d^i \cdot C_{l/d}^i \cdot C_{steel}^i \cdot C_{mc}^i \cdot C_t^i \cdot f_{core,i}\right)/n \quad (2)$$

in which:

- α_2 depends on the drilling direction (α_2 = 1.15 for drilling perpendicular to the direction of casting concrete, and α_2 = 1.05 for perforations parallel to the direction of casting concrete);
- C_{dia} takes into account the diameter of the core: 1.06 for the core diameter with d = 50 mm, 1.00 for d = 100 mm, and 0.98 for d = 150 mm;
- C_d takes into account the disturbance during drilling operations. It presupposes the following equation:

$$C_d = -0.006 \cdot f_{core} + 1.26 \quad (3)$$

  where f_{core} is expressed in MPa;
- $C_{l/d}$ takes into account the ratio height/diameter (l/d) of core. It presupposes the following equation:

$$C_{l/d} = 0.045 \cdot (l/d)^3 - 0.308 \cdot (l/d)^2 + 0.766 \cdot (l/d) + 0.340 \quad (4)$$

  in which d is the core diameter and l is its height.
- C_{steel} takes into account the presence of reinforcing bars. According to the British Standards Institution (1991), for cores containing a single bar, $C_{steel}^i = 1 + 1.5\frac{\phi_r \cdot b}{d \cdot l}$, where ϕ_r is the diameter of the reinforcement. b is the distance of the axis of the bar from nearer the end of the specimen; d and l are the diameter and the length of the specimen after end-preparation by grinding or capping, respectively. The results should be ignored if the correct strength varies more than 10% [1]. In the case of several bars: $C_{steel}^i = 1 + 1.5\frac{\sum \phi_r \cdot b}{d \cdot l}$. Personally, I believe that, in general, it would be advisable to always discard the cores that incorporate reinforcing bars inside.
- C_{mc} takes into account the moisture condition of the core. According to ACI 214.4R-03 [17], the following values are suggested: (i) as-received, C_{mc} = 1.00; (ii) soaked 48 h, C_{mc} = 1.09; (iii) air dried, C_{mc}= 0.96.
- C_t takes into account the age of the concrete. For young concrete, that is, if the tests are carried out before 28 days of curing, then the value suggested by EN 1992-1-1 [7] could be used: $C_t^i = \frac{1}{e^{s(1-\sqrt{28/t})}}$, where s is a coefficient which depends on the type of cement. (i) s = 0.20 for cement of strength classes CEM 42.5 R; CEM 53.5 N; CEM 53.5 R (Class R). (ii) s = 0.25 for cement of strength classes CEM 32.5 R; CEM 42.5 N (Class N). s = 0.38 for cement of strength classes CEM 32.5 N (Class S). This expression allows us to extrapolate the strength measured before 28 days (of young concrete) to that at 28 days. Some authors suggest also using this coefficient for concrete with an age t > 28 days [10] to take into account the greater strength of concrete after 28 days.

3. Potential Strength Assessment

3.1. Concrete Society Technical Report 11

The Concrete Society Technical Report 11 [1] proposes an expression to estimate the potential strength of concrete, taking corrections into account for differences in orientation, composition, compaction, and the curing history between the concrete core and the concrete considered as the average standard cube strength at 28 days. Specifically, when previous conditions are normal [1–3], the estimate of the potential strength can be carried out using the following equation:

$$R_{c,p} = f_{core}\frac{D}{1.5 + 1/\lambda} \quad (5)$$

where

- $R_{c,p}$ is the estimated strength;
- D is a parameter depending on the direction of perforation (D = 3.25 for the core drilled in a horizontal direction, and D = 3.00 for the core drilled in a vertical direction);
- λ is the core slenderness (the ratio between length and diameter);
- f_{core} is the core strength.

If the previous conditions are abnormal, a procedure is scrutinised in report 11 to correct the results of Equation (5), introducing a coefficient that takes into account the presence of steel in the test core and a correction factor that takes into account the influence of excess voidage.

With reference to the latter, in [1], two independent estimation methods are recommended: (i) density test results and (ii) visual means.

(a) From density test results

The excess voidage of the core is:

$$EV = \frac{D_p - D_a}{D_p - k \times 1000} 100\% \tag{6}$$

In Equation (6), D_p is the potential density, D_a is the actual density, and k is the factor of the voids in the core (resulting from imperfection compaction and being filled with water when D_a is measured and assumed to be 0.5).

Therefore, in report 11, the strength multiplying factor (C^i_{EV}, variable from 1 to 1.51) is proposed to account for the application of Equation (5) [1].

$$R_{c,p} = f_{core} \frac{D}{1.5 + 1/\lambda} C_{EV} \tag{7}$$

(b) By visual means

This method compares the number and size of exposed voids on the drilled surface of the same core with those displayed in some figures contained in report 11 or in BS 1881-120 [3]. Thus, based on the assumption that the potential voidage is 0.5%, it is possible to estimate the excess voidage of the core by comparing the number and size of the voids exposed on the drilled surface of the core with those displayed in Figure 3a–e of report 11 [1].

3.2. Pucinotti Method

In this section, the analytic expression introduced in Section 2 is updated with the addition of new coefficients in order to consider the influence of excess voidage and addition of water to the cement mixer:

$$f_{cm,p,P} = \left(\sum_{i=1}^{n} \alpha_2^i \cdot C^i_{dia} \cdot C^i_d \cdot C^i_{l/d} \cdot C^i_{steel} \cdot C^i_{mc} \cdot C^i_t \cdot C^i_{H_2O} \cdot C^{\,i}_{com} \cdot f_{\,carota,i} \right) / n \tag{8}$$

The following additional parameters are considered:

- C_{H_2O} takes into account the addition of water to the cement mixer. According to Coppola et al. [10], the following value is suggested: $C^i_{H_2O} = \frac{1}{1-0.007 \cdot \left(\frac{Acq}{9.81} \right)}$, where A_{cq} is the quantity of water (expressed in N) added to the mix for each m^3 of concrete.
- C^i_{com} takes into account the influence of excess voidage. It is therefore evident how compaction plays an important role in reducing the strength of in situ concrete when compared to the potential strength.

With regards to the influence of excess voidage, a new estimate procedure is introduced in the following section.

Influence of Excess Voidage

As already mentioned, when the potential density (unit weight) of cube (or cylindric) specimens is not available, report 11 [1] suggests comparing the number and size of voids exposed on the drilled surface of the same core with those displayed in some figures contained in report 11. The method consists of a visual evaluation of the compactness of the concrete estimating the percentage of excess voids in the test specimen with respect to those in the reference specimens, i.e., comparing the core surface with photos of cores of different masked voidage content in BS 1881-120 (Figure 1a–e) [1,3] by measuring excess voidage, which is the amount by which actual voidage exceeds the voidage of a well-made cube of the same concrete.

British standards suggest that *where the description needs to be amplified, this shall be done by reference to the following terms:*

(a) *Small void. A void measuring not less than 0.5 mm and not more than 3 mm across in any direction.*
(b) *Medium void. A void having a dimension greater than 3 mm but not greater than 6 mm.*
(c) *Large void. A void having a dimension greater than 6 mm.*
(d) *Honeycombing. Interconnected voids arising from, for example, inadequate compaction or a lack of mortar.*

4. Experimental Program

An experimental campaign was carried out on two groups of cores, some of which were prepared ad hoc.

In this section, the first and most significant results are presented and commented on.

4.1. First Series

In this first series, only the criterion of report 11 [1] is applied: the comparison of the number and the size of the voids exposed on the drilled surface of the same core with those displayed in some figures contained in the report. In this case, Equation (6) of Section 3 was not applicable; in fact, in some cores, the unit weight of concrete was higher than that of the concrete acceptance testing.

In particular, tests were carried out on cores extracted from two different structures assigned as second and third groups, respectively.

The structures were designed with a concrete strength class of C25/30 (design strength class—DSC); the acceptance testing of hardened concrete was carried out according to the Italian code [29] and returned the strength classes shown in Tables 1 and 2 (indicated as actual strength classes (ASC) in column 12).

Specifically, these are reinforced concrete (R.C.) tunnels and composite RC-steel bridges for which a legal dispute has arisen with reference on the mechanical properties of the concrete. Therefore, no further information can be provided at this time.

All cores were carefully examined, prepared by grinding, and tested in compression using standard procedures.

Compressive strength variability results were detailed in [12], where it was observed that (shown in Tables 1 and 2).

- Second group: The percentage difference between two cores obtained from the same drilling varies from 0.05% to more than 18.50%, and the result obtained by varying the extraction point varies from 6.59% to 19.40%;
- Third group: The percentage difference between two cores obtained from the same drilling varies from 3.58% to more than 34.31%, and the result obtained by varying the extraction point varies from 2.42% to 27.65%.

Table 1. Second group.

Cores	Unit Weight (kN/m^3)	*d* (mm)	*l* (mm)	*l/d*	*Ac* (mm^2)	Cor. Dir.	f_{core} (N/mm^2)	$f^{med}{}_{core}$ (N/mm^2)	Diff. (%)	DSC	ASC
MSC 1 a	22.692	103	101	0.97	8397	v	27.70				
MSC 1 b	22.741	103	95	0.92	8381	v	32.48	30.09	15.89		
MSC 1 c	22.814	104	98	0.94	8462	v	32.38				
MSC 1 d	22.734	105	95	0.91	8626	v	35.25	33.82	8.49		
MSC 1 e	23.377	104	101	0.97	8462	v	33.36				
MSC 1 f	22.950	104	104	1.00	8446	v	36.28				
MSC 1 g	23.513	104	98	0.94	8462	v	40.13	36.59	18.50	C25/30	C32/40
MSC 2 a	22.611	104	98	0.95	8462	v	34.36				
MSC 2 b	22.928	104	98	0.94	8446	v	32.68	33.52	5.01		
MSC 2 c	23.130	104	101	0.97	8462	v	38.08				
MSC 2 d	22.725	104	98	0.94	8462	v	38.10	38.09	0.05	C25/30	C35/45
ARC 1 a	22.588	104	97	0.94	8462	v	32.66				
ARC 1 b	22.591	104	93	0.89	8462	v	30.39	31.53	7.20		
ARC 1 c	22.602	104	95	0.92	8462	v	29.24				
ARC 1 d	22.534	104	96	0.92	8462	v	32.66	30.95	11.05		
ARC 1 e	23.056	104	98	0.95	8462	v	33.47				
ARC 1 f	22.948	104	98	0.94	8430	v	37.43	35.45	11.17	C25/30	C32/40
CVD a	23.377	104	101	0.97	8462	h	31.08				
CVD b	23.310	104	98	0.95	8462	h	30.54	30.81	1.75		
CVD c	23.613	104	98	0.94	8479	h	32.52				
CVD v	23.632	104	98	0.94	8446	h	33.32	32.92	2.43	C25/30	C30/37

d = core diameter; *l* = core height; Cor. Dir = drilling direction; f_{core} = core strength; $f^{med}{}_{core}$ = mean value of core strength; Diff. = percentage difference; DSC = design strength class; ASC = actual strength classes.

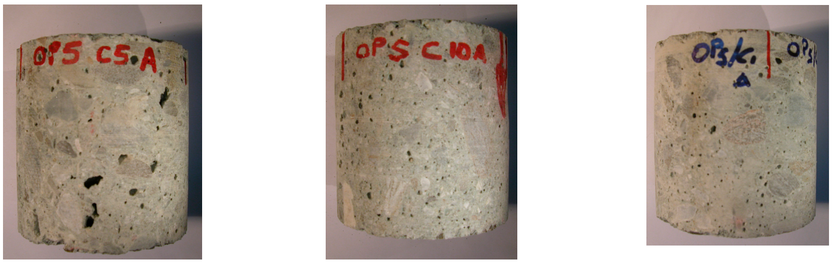
Table 2. Third group.

Cores	Unit Weight (kN/m^3)	d (mm)	l (mm)	l/d	Ac (mm^2)	Cor. Dir	f_{core} (N/mm^2)	f^{med}_{core} (N/mm^2)	Diff. (%)	DSC	ASC
CVD a	23.898	104	93	0.89	8446	h	32.24				
CVD b	24.170	104	93	0.89	8462	h	36.43	34.34	12.20		
CVD c	24.396	104	93	0.89	8446	h	35.90				
CVD d	23.157	104	97	0.94	8446	h	39.51				
CVD e	23.247	104	98	0.94	8462	h	39.46	38.29	9.30	C25/30	C32/40
CMD a	22.786	104	104	1.00	8413	h	23.43				
CMD b	22.941	104	98	0.94	8446	h	24.66	24.05	5.12		
CMD c	23.647	104	98	0.94	8462	h	30.98				
CMD d	23.404	104	98	0.94	8462	h	32.37	31.68	4.39	C25/30	C30/37
MSC 1 a	22.058	104	98	0.94	8446	v	33.99				
MSC 1 b	22.789	104	98	0.94	8462	v	39.75	36.87	15.62		
MSC 1 c	22.896	104	98	0.94	8462	v	46.61				
MSC 1 d	23.030	104	98	0.94	8462	v	49.30	47.96	5.61	C25/30	C35/45
MDC 1 a	23.112	104	102	0.98	8446	v	42.68				
MDC 1 b	22.800	104	102	0.98	8462	v	41.18	41.93	3.58		
MDC 1 c	22.310	104	104	1.00	8462	v	36.14				
MDC 1 d	23.310	104	98	0.95	8462	v	47.22				
MDC 1 e	22.790	104	102	0.98	8462	v	39.48	40.95	8.16	C25/30	C35/45
ARC 2 a	22.428	104	104	1.00	8462	v	28.05				
ARC 2 b	22.611	104	98	0.95	8462	v	25.10	26.58	11.10		
ARC 2 c	23.105	104	93	0.89	8479	v	37.01				
ARC 2 d	22.609	104	97	0.93	8462	v	29.08	33.05	24.00		
ARC 2 e	22.724	104	96	0.93	8462	v	39.34				
ARC 2 f	22.489	104	97	0.93	8479	v	27.82	33.58	34.31	C25/30	C32/40
ARC 3 a	22.848	104	98	0.95	8446	v	28.38				
ARC 3 b	22.802	104	104	1.00	8462	v	29.94	29.16	5.35		
ARC 3 c	22.801	104	96	0.93	8462	v	29.29				
ARC 3 d	23.121	104	97	0.93	8462	v	31.84	30.57	8.34	C25/30	C32/40

d = core diameter; l = core height; Cor. Dir = drilling direction; f_{core} = core strength; f^{med}_{core} = mean value of core strength; Diff. = percentage difference; DSC = design strength class; ASC = actual strength classes.

Experimental Results

It should be pointed out that, even within the same drilling, significant variations in the percentage of voids can be recorded. These are sufficient to move the specimen from class 2 to class 4. As an example, the void assessment of a drilling of the second group is shown in Figure 1. In detail, from the drilling of 440 mm of depth with a diameter of 94 mm, 3 cores were obtained: MSC-1e, MSC-1f, and MSC-1g. The estimated void is equal to 3% for core MSC-1e (on the left of Figure 1), falling to 1.5% for core MSC-1f (in the centre) and decreasing further to 0.5% for core MSC-1g (on the right). These results are consistent with the variations in compressive strength of the same cores within the drilling indicated as Drilling n.3 in [2] (33.36 MPa, 36.28 MPa, and 40.13 MPa). This confirms that all these anomalies bring about not only a lack of homogeneity and variations in the grade of compactness and resistance in different sections of the structural element, but can cause variations in the resistance even within the same section. Figure 2 shows the assessment of voids obtained by varying the extraction point of the cores in the second group; it is easy to verify as the percentage of voids varies from 0.5% to 3.0%.



(**a**) (**b**) (**c**)

Figure 1. Assessment of voids within the same drilling: (**a**) Specimen MSC-1e-V = 3%; (**b**) Specimen MSC-1f-V = 1.5%; (**c**) Specimen MSC-1g-V = 0.5%.

(**a**) (**b**) (**c**) (**d**)

Figure 2. Assessment of voids for different points of core extraction: (**a**) V = 0%; (**b**) V = 0.5%; (**c**) V = 1.5%; (**d**) V = 3.0%.

Tables 3 and 4 report the potential strength estimation results obtained by using the Concrete Society technical report (CSTR), while Tables 5 and 6 show the results obtained using the proposed formation when the values suggested by the Concrete Society report 11 for the corrective factor CEV are adopted.

Table 3. Second croup—Estimated Class by CSTR procedure.

Cores	D	$R_{c,a}$	$R^{med}{}_{c,a}$	D	$R_{c,p}$	C_{EV}	$R^{med}{}_{c,p}$	ESC
MSC 1 a	2.30	25.19		3.00	32.86			
MSC 1 b	2.30	28.82		3.00	37.59			
MSC 1 c	2.30	29.10		3.00	37.96			
MSC 1 d	2.30	31.14		3.00	40.62			
MSC 1 e	2.30	30.37		3.00	39.61			
MSC 1 f	2.30	33.39		3.00	43.55			
MSC 1 g	2.30	35.99	30.57	3.00	46.94	1.00	39.88	C30/37
MSC 2 a	2.30	30.89		3.00	40.30			
MSC 2 b	2.30	29.33		3.00	38.26			
MSC 2 c	2.30	34.62		3.00	45.16			
MSC 2 d	2.30	34.17	32.25	3.00	44.57	1.04	43.75	C32/40
ARC 1 a	2.30	29.24		3.00	38.14			
ARC 1 b	2.30	26.71		3.00	34.83			
ARC 1 c	2.30	25.94		3.00	33.83			
ARC 1 d	2.30	29.05		3.00	37.89			
ARC 1 e	2.30	30.09		3.00	39.25			
ARC 1 f	2.30	33.61	29.11	3.00	43.84	1.04	39.48	C30/37
CVD a	2.50	30.75		3.25	39.98			
CVD b	2.50	29.88		3.25	38.85			
CVD c	2.50	31.73		3.25	41.25			
CVD v	2.50	32.53	31.22	3.25	42.30	1.04	42.22	C32/40

D = parameter depending on the direction of perforation; $R_{c,a}$ = estimated actual strength; $R^{med}{}_{c,a}$ = mean value; $R_{c,p}$ = estimated potential strength; $R^{med}{}_{c,p}$ = mean value; C_{EV} = corrective factor.

Table 4. Third group—estimated strength class (ESC) by CSTR procedure.

Cores	D	$R_{c,a}$	$R^{med}{}_{c,a}$	D	$R_{c,p}$	C_{EV}	$R^{med}{}_{c,p}$	ESC
CVD a	2.50	30.75		3.25	39.98			
CVD b	2.50	34.75		3.25	45.17			
CVD c	2.50	34.26		3.25	44.53			
CVD d	2.50	38.51		3.25	50.07			
CVD e	2.50	38.50	35.35	3.25	50.05	1.04	47.80	C35/45
CMD a	2.50	23.45		3.25	30.48			
CMD b	2.50	24.07		3.25	31.29			
CMD c	2.50	30.21		3.25	39.28			
CMD d	2.50	31.57	29.56	3.25	41.04	1.13	40.14	C32/40
MSC 1 a	2.30	30.53		3.00	39.83			
MSC 1 b	2.30	35.69		3.00	46.56			
MSC 1 c	2.30	41.82		3.00	54.55			
MSC 1 d	2.30	44.25	36.77	3.00	57.72	1.00	49.66	C35/45
MDC 1 a	2.30	39.02		3.00	50.90			
MDC 1 b	2.30	37.62		3.00	49.07			
MDC 1 c	2.30	33.21		3.00	43.32			
MDC 1 d	2.30	42.47		3.00	55.40			
MDC 1 e	2.30	36.08	37.68	3.00	47.06	1.00	49.15	C35/45
ARC 2 a	2.30	25.81		3.00	33.66			
ARC 2 b	2.30	22.57		3.00	29.44			
ARC 2 c	2.30	32.48		3.00	42.36			
ARC 2 d	2.30	26.00		3.00	33.91			
ARC 2 e	2.30	35.07		3.00	45.74			
ARC 2 f	2.30	24.83	28.19	3.00	32.39	1.04	37.70	C30/37
ARC 3 a	2.30	25.54		3.00	33.31			
ARC 3 b	2.30	27.52		3.00	35.90			
ARC 3 c	2.30	26.14		3.00	34.10			
ARC 3 d	2.30	28.44	26.50	3.00	37.10	1.04	36.51	C25/30

D = parameter depending on the direction of perforation; $R_{c,a}$ = estimated actual strength; $R^{med}{}_{c,a}$ = mean value; $R_{c,p}$ = estimated potential strength; $R^{med}{}_{c,p}$ = mean value; C_{EV} = corrective factor; ESC = estimated strength class by CSTR procedure.

Table 5. Second group—estimate strength class (ESC) by Pucinotti procedure.

Cores	α_2	C_d	C_{dia}	C_{mc}	$f_{c,P}$ (MPa)	$f_{cm,P}$ (MPa)	$f_{ck,in\ situ,P}$ (MPa)	$C_{com,m}$	$f_{ck,p,P}$ (MPa)	ESC
MSC 1 a	1.15	1.09	1.21	1.00	42.05					
MSC 1 b	1.15	1.07	1.13	1.00	44.91					
MSC 1 c	1.15	1.07	1.17	1.00	46.33					
MSC 1 d	1.15	1.05	1.12	1.00	47.45					
MSC 1 e	1.15	1.06	1.21	1.00	49.19					
MSC 1 f	1.15	1.04	1.25	1.00	54.34					
MSC 1 g	1.15	1.02	1.16	1.00	54.60	48.41	43.41	1.00	43.41	C32/40
MSC 2 a	1.15	1.05	1.17	1.00	48.67					
MSC 2 b	1.15	1.06	1.16	1.00	46.51					
MSC 2 c	1.15	1.03	1.21	1.00	54.46					
MSC 2 d	1.15	1.03	1.16	1.00	52.45	50.52	44.52	1.04	46.30	C35/45
ARC 1 a	1.15	1.06	1.16	1.00	46.17					
ARC 1 b	1.15	1.08	1.10	1.00	41.48					
ARC 1 c	1.15	1.08	1.13	1.00	41.14					
ARC 1 d	1.15	1.06	1.14	1.00	45.39					
ARC 1 e	1.15	1.06	1.17	1.00	47.65					
ARC 1 f	1.15	1.04	1.16	1.00	51.90	45.62	39.62	1.04	41.21	C32/40
CVD a	1.05	1.07	1.21	1.00	42.38					
CVD b	1.05	1.08	1.17	1.00	40.49					
CVD c	1.05	1.06	1.16	1.00	42.30					
CVD v	1.05	1.06	1.17	1.00	43.24	42.10	36.10	1.04	37.55	C30/37

α_2 = parameter depending on the drilling direction; C_d, takes into account the disturbance during drilling operations.; C_{dia}, takes into account the diameter of the core; C_{mc} = takes into account the moisture condition of the core; $f_{c,P}$ = in situ compressive strength; $f_{cm,P}$ = mean value; $f_{ck,in\ situ,P}$ = in situ characteristic strength assessment; $C_{com,m}$ = takes into account the influence of excess voidage; $f_{ck,p,P}$ = potential characteristic strength assessment; ESC = estimate strength class by Pucinotti procedure.

Table 6. Third group—estimate strength class by Pucinotti procedure.

Cores	α_2	C_d	C_{dia}	C_{mc}	$f_{c,P}$ (MPa)	$f_{cm,P}$ (MPa)	$f_{ck,in\ situ,P}$ (MPa)	$C_{com,m}$	$f_{ck,p,P}$ (MPa)	ESC
CVD a	1.05	1.07	1.10	1.00	39.63					
CVD b	1.05	1.04	1.10	1.00	43.73					
CVD c	1.05	1.04	1.10	1.00	43.27					
CVD d	1.05	1.02	1.16	1.00	49.25					
CVD e	1.05	1.02	1.16	1.00	49.32	45.04	40.04	1.04	41.64	C32/40
CMD a	1.05	1.12	1.25	1.00	34.45					
CMD b	1.05	1.11	1.16	1.00	33.53					
CMD c	1.05	1.07	1.16	1.00	40.60					
CMD d	1.05	1.07	1.16	1.00	42.09	37.67	32.67	1.13	36.92	C30/37
MSC 1 a	1.15	1.06	1.17	1.00	48.13					
MSC 1 b	1.15	1.02	1.16	1.00	54.39					
MSC 1 c	1.15	0.98	1.16	1.00	61.06					
MSC 1 d	1.15	0.96	1.16	1.00	63.60	56.79	51.79	1.00	51.79	C40/50
MDC 1 a	1.15	1.00	1.23	1.00	60.37					
MDC 1 b	1.15	1.01	1.22	1.00	58.63					
MDC 1 c	1.15	1.04	1.24	1.00	53.92					
MDC 1 d	1.15	0.98	1.17	1.00	62.05					
MDC 1 e	1.15	1.02	1.22	1.00	56.84	58.36	53.36	1.00	53.36	C40/50
ARC 2 a	1.15	1.09	1.25	1.00	43.95					
ARC 2 b	1.15	1.11	1.17	1.00	37.43					
ARC 2 c	1.15	1.04	1.10	1.00	48.50					
ARC 2 d	1.15	1.09	1.15	1.00	41.80					
ARC 2 e	1.15	1.02	1.14	1.00	52.92					
ARC 2 f	1.15	1.09	1.15	1.00	40.09	44.11	39.11	1.04	40.68	C32/40
ARC 3 a	1.15	1.09	1.17	1.00	41.66					
ARC 3 b	1.15	1.08	1.25	1.00	46.32					
ARC 3 c	1.15	1.08	1.15	1.00	41.86					
ARC 3 d	1.15	1.07	1.15	1.00	44.97	43.70	38.70	1.04	40.25	C32/40

α_2 = parameter depending on the drilling direction; C_d, takes into account the disturbance during drilling operations.; C_{dia}, takes into account the diameter of the core; C_{mc} = takes into account the moisture condition of the core; $f_{c,P}$ = in situ compressive strength; $f_{cm,P}$ = mean value; $f_{ck,in\ situ,P}$ = in situ characteristic strength assessment; $C_{com,m}$ = takes into account the influence of excess voidage; $f_{ck,p,P}$ = potential characteristic strength assessment; ESC = estimate strength class by Pucinotti procedure.

Table 7 reports the comparison between the actual strength classes (ASC) of concrete and estimated strength classes (ESC) obtained via the application of the CSTR procedure and Pucinotti, respectively.

Table 7. Comparison of results.

Specimen	ASC	CSTR ESC	Pucinotti ESC	Specimen	ASC	CSTR ESC	Pucinotti ESC
Second Group				Third Group			
MSC 1 a				CVD a			
MSC 1 b				CVD b			
MSC 1 c				CVD c			
MSC 1 d				CVD d			
MSC 1 e				CVD e	C32/40	C35/45	C32/40
MSC 1 f				CMD a			
MSC 1 g	C32/40	C30/37	C32/40	CMD b			
MSC 2 a				CMD c			
MSC 2 b				CMD d	C30/37	C32/40	C30/37
MSC 2 c				MSC 1 a			
MSC 2 d	C35/45	C32/40	C35/45	MSC 1 b			
ARC 1 a				MSC 1 c			
ARC 1 b				MSC 1 d	C35/45	C35/45	C40/50
ARC 1 c				MDC 1 a			
ARC 1 d				MDC 1 b			
ARC 1 e				MDC 1 c			
ARC 1 f	C32/40	C30/37	C32/40	MDC 1 d			
CVD a				MDC 1 e	C35/45	C35/45	C40/50
CVD b				ARC 2 a			
CVD c				ARC 2 b			
CVD v	C30/37	C32/40	C30/37	ARC 2 c			
				ARC 2 d			
				ARC 2 e			
				ARC 2 f	C32/40	C30/37	C32/40
				ARC 3 a			
				ARC 3 b			
				ARC 3 c			
				ARC 3 d	C32/40	C25/30	C32/40

ASC = actual strength classes; CSTR—ESC = estimated strength class by CSTR procedure; Pucinotti—ESC = estimate strength class by Pucinotti procedure.

The comparison reported in Table 7 shows that the proposed formulation is able to estimate, with a good degree of approximation, the actual value of the potential strength of the concrete.

In fact, the red letters indicate that the procedure has failed in the core strength estimation; with reference to the specimens appointed as MSC 1, the actual strength class is equal to C32/40. The estimated strength class via the application of the CSTR procedure is equal to C30/37 (indicated in red letters).

The estimated strength class obtained via the application of the Pucinotti procedure coincides with the actual strength class (C32/40) and is indicated in black letters.

4.2. Second Series

As highlighted earlier, the compaction of the concrete plays an important role in reducing the strength of in situ concrete compared to that of the cubes (or cylinders) arranged during the casting phase. This section proposes an effective method to calculate the excess voidage of the in situ concrete. The proposed methodology provides, via computed axial tomography (CAT) scan of the cores, a direct estimate of the percentage of voids.

The system used is the XTH225 series from Nikon, with the following technical specifications: X-ray Source XT H225

- Type;
- Target Options—Reflection Target, Transmission Target, Multimetal Target;
- Max. Power—225 W;
- Min. Focal Spot—1 µm;

System

- Max. CT Swept Diameter—280 mm;
- Max. FID—970 mm nominal;
- FID Type—Moveable;

- Max. Sample Weight—15 kg;

Detector

- Max. Pixel Matrix—2880 × 2880;
- Min. Pixel Size—150 µm;
- Max. Frame Rate—30 fps;
- Type—ASTM E2597 Flat Panel;

Cabinet

- Length—1830 mm;
- Width—875 mm;
- Height—1987 mm;
- Weight—2400 kg.

This is an efficient tool to provide valuable information about the measurement of the internal features of materials in detail for material verification and analysis (e.g., structure, porosity, and defects).

Studies are currently underway, but in the following, by way of example, the first results of experimental applications carried out on cores of concrete that confirm the efficacy of the introduced procedure are presented.

For this purpose, a second series of experimental tests was carried out on cores extracted from a concrete wall built ad hoc. The concrete wall was built with 3 different types of concrete strength: class concrete C28/35 (Cls1), class concrete C40/50 (Cls2), and class concrete C25/30 (Cls3). For the wall portions built with class concrete C28/25 and C40/50, three different times of vibration of fresh concrete during casting were performed, while for class concrete C25/30, two different times of vibration were used. This produced three and two different degrees of concrete compaction, respectively.

Figure 3 shows a side view of the concrete wall, indicating its geometry and the points of drilling. Table 8 shows in detail the composition of the concrete used for each strength class, while Figure 4 shows all specimens subjected to experimental tests. In detail, specimens appointed as Cls 1 in Table 8 were designed with concrete grade C28/35, with compaction decreasing from specimens 1/1 to specimens l/3 (see Figure 3). Specimens appointed as Cls 2 were designed with concrete grade C40/50, with compaction decreasing from specimens 2/1 to specimen 2/3. Specimens appointed as Cls 3 were designed with concrete grade C25/30, with compaction decreasing from specimens 3/1 to specimens 3/2.

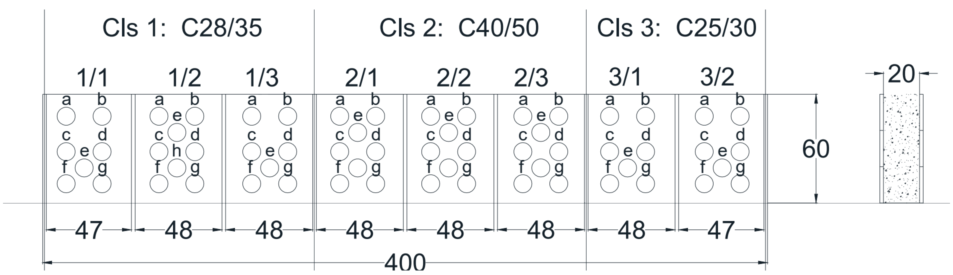


Figure 3. Concrete wall.

(**a**)

Figure 4. *Cont.*

(**b**)

(**c**)

(**d**)

(**e**)

(**f**)

(**g**)

(**h**)

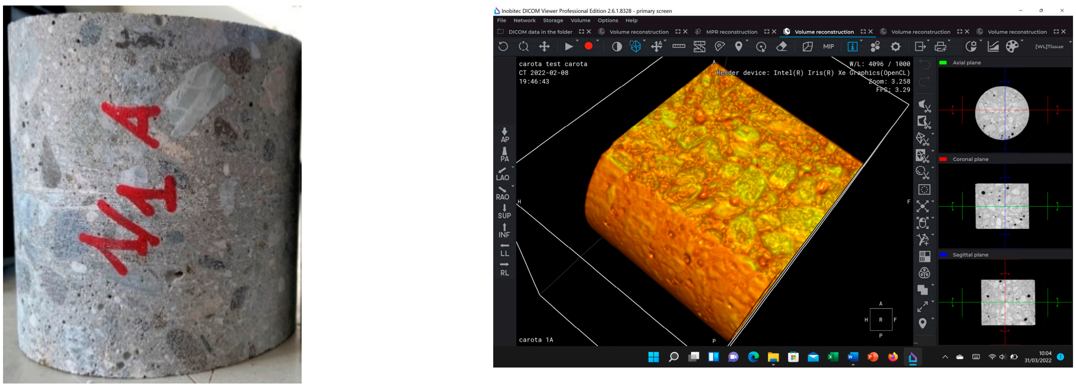
Figure 4. Cores extracted from concrete wall via drilling: (**a**) Specimens 1/1 (**a**–**g**); (**b**) Specimens 1/2 (**a**–**g**); (**c**) Specimens 1/3 (**a**–**g**); (**d**) Specimens 2/1 (**a**–**g**); (**e**) Specimens 2/2 (**a**–**g**); (**f**) Specimens 2/3 (**a**–**g**); (**g**) Specimens 3/1 (**a**,**b**,**d**–**g**); (**h**) Specimens 3/2 (**a**–**g**). All cores have diameters of 94 mm and variable heights (from 85 to 103 mm).

Table 8. Mix design.

	Type of Cement	Water [l/m^3]	Cement Content [kN/m^3]	Ratio a/c	Plasticizer [l/m^3]	f_{ck} [MPa]	R_{ck} [MPa]	Consistency Classes	Sand Size 0–8 mm [Kg/m^3]	Aggregate Size 4–16 mm [Kg/m^3]	Aggregate Size 10–20 mm [Kg/m^3]	Maximum Aggregate Diameter [mm]	Unit Weight [kN/m^3]
Cls1	CEM II/A-LL 42.5 R	185	4.00	0.46	3.2	28	35	S4	9.98	2.18	5.99	20	24.03
Cls2	CEM II/A-LL 42.5 R	185	5.30	0.35	4.2	40	50	S4	9.31	2.03	5.59	20	24.12
Cls3	CEM II/A-LL 42.5 R	185	3.50	0.53	2.8	25	30	S4	10.24	2.23	6.14	20	23.99

Experimental Results

Figure 5 shows the results of one of the tests using a medical computed axial tomography (CAT) scan. It is possible to see how the instrument verifies the actual presence of voids in the specimen under investigation; even in this case, the estimation of void volume is highly dependent on the high sensitivity of the instrument to assess the density of air.



(**a**) (**b**)

Figure 5. Specimen 1/1 A of second series: (**a**) photo of the specimen; (**b**) computed axial tomography (CAT) of the specimen.

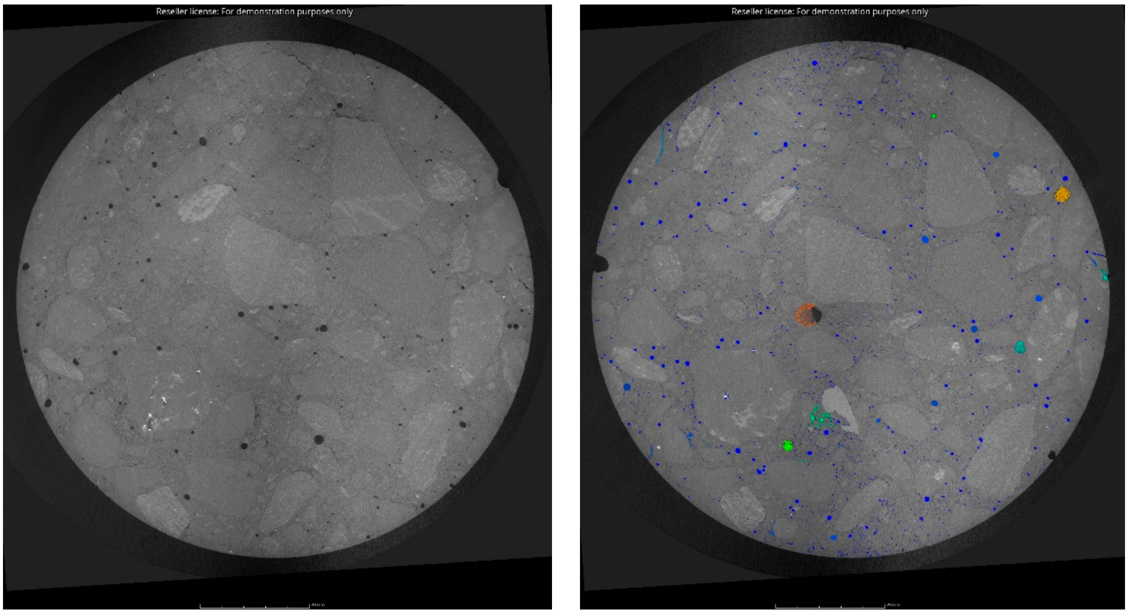
Figure 6 instead shows the results using a machine created for industrial use with a resolution of 22 µm, capable of perfectly estimating the density of voids and, therefore, capable of identifying the presence of voids and of estimating their percentage.

In this case, for the specimen appointed in Figure 6 as Specimen 1/1F, a percentage of voids equal to 1.4% was estimated. This specimen has a unit weight of 23.68 kN/m^3; this value is completely in line with that obtained from Equation (6) of Section 3.1. Applying the density test method of report 11, a value of EV = 1.41% is obtained.

Figure 7 shows the scan performed for the specimen, appointed as 2/1 H. In this case, the maximum size of the voids is greater than in the previous case, and the percentage reaches a value of 2.75%. The specimen 2/2 H has a unit weight of 23.50 kN/m^3. In this case, the application of Equation (6) returns EV = 2.46%.

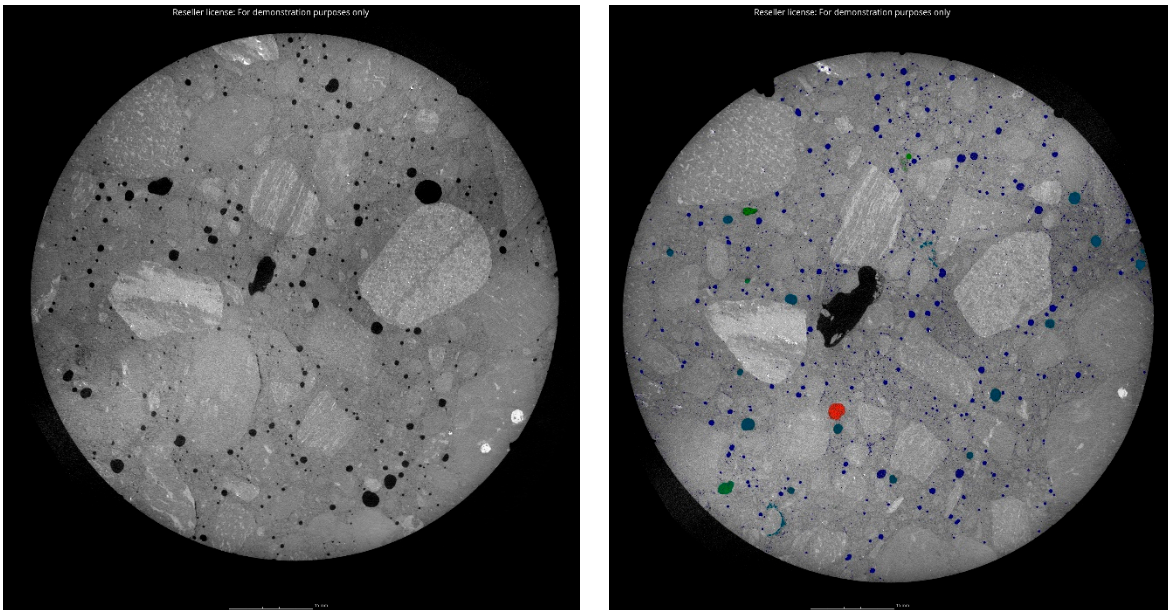
The results are consistent with the resistances of the cores; in fact, specimen 2/1H showed lower resistance than the 1/1F sample (equal to 43.12 MPa and 48.18 MPa, respectively).

When taking this into account, the resistance values obtained from the cores were in line with those relating to acceptance controls; these elaborations are still in progress. The results will be the subject of a forthcoming paper.



(**a**) (**b**)

Figure 6. Specimen 1/1 F of second series; automatic detection and measurement of voids: (**a**,**b**) CAT performed at two different depths.



(**a**) (**b**)

Figure 7. Specimen 2/1 H of second series; automatic detection and measurement of voids (**a**,**b**) CAT performed at two different depths.

5. Conclusions

In the paper, both the variability of concrete in the same drilling and a new methodology able to estimate the percentage of voids using a computed axial tomography scan (CAT) scan are presented. Moreover, while accounting for such variability, the paper introduces a new formulation to assess both the in situ and potential characteristic strengths of concrete.

Results show noticeable variations in the percentage of voids within the same drilling. Moreover, the proposed formulation can estimate the actual value of both in situ and potential characteristic strength of concrete with a reasonable degree of approximation.

The application of the visual method (proposed by report 11 of the Concrete Society [11] and BS 1881-120 [12]) is very approximate. Its application loses validity when a visual evaluation of the compactness of concrete is performed based on comparison with a photo.

The conduction of a computed axial tomography (CAT) scan leads to extremely precise results and also evaluates the percentage of voids in different sections of the same core.

At this point, it is possible estimate the mean value of the percentage of voids among those obtained in all scanned sections via CAT scan; this is a more reliable estimate of the percentage of voids in a concrete core.

The undeniable advantage of the new procedure is that it allows you to perform a large number of scans on a single specimen, therefore allowing you to estimate the average value of the percentage of voids present in the various scanned sections. On the contrary, the traditional technique, based on the comparison with (even dated) photographs, still presents a strong limit in terms of the effective representativeness of the estimates made.

Further studies are underway to recalibrate the correction coefficients as a function of the percentage of voids obtained by a CAT scan.

The ongoing activity concerns the implementation of a procedure aimed at: (i) correlating the percentage of voids with the potential strength of concrete and; (ii) determining the optimal number of scansions (CAT scans) performed in each core.

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