

TECHNICAL PAPER

Compressive strength of core specimens drilled from concrete test cylinders

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Abstract

The compressive strength of concrete is highly influenced by the properties of test specimens, such as size and moisture content. This paper presents the results of compression tests on more than 650 test specimens made with four different concrete types, which are mainly air-entrained. The differences in compressive strength between different types of concrete specimens were investigated with similar compaction and curing conditions. The tested specimens were 50 × 50 mm, 80 × 80 mm, 100 × 100 mm, and 150 × 300 mm cores, which were drilled from the cast cylinders. In addition, 150-mm cubes, 100 × 100 mm and 150 × 300 mm cylinders were included in the test programme. The ratios of compressive strength between different core sizes and core strength comparability to the cast specimens were found to be strongly dependent on the concrete type. Drilling was found to have a clear weakening effect on obtained compressive strength. The conversion factors for the compressive strength between the core and the same size cast specimen was proposed for 150 × 300 mm and 100 × 100 mm specimen sizes.

KEYWORDS

air-entrained, concrete, compressive, strength, core, cylinder, size effect, testing

1 | INTRODUCTION

Compressive strength is one of the most important properties of concrete. Furthermore, it is commonly considered as a reference for many other properties, such as the tensile strength and elastic modulus of concrete. Compressive strength also gives a good overall picture of the quality of concrete.¹ For the assessment of concrete's

compressive strength from cast-in-situ or precast concrete, drilled cores are widely used. When compared to other assessment methods such as rebound hammer tests, ultrasonic pulse velocity tests and concrete pullout tests, core testing probably gives the best estimate for the in-situ compressive strength of concrete. Therefore, core testing is also often used for the calibration of other methods.² However, the results of the core tests should be interpreted with care, due to several variables such as diameter, moisture conditions, and slenderness, that is, the length-to-diameter ratio of test specimens. Furthermore, the compaction and the hardening conditions of the core specimens are different from the standard test

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specimens. Due to drilling, the surface of the specimen differs between the cores and the standard specimens. All these features may have some effect on the test result.³ When estimating the compressive strength of concrete, it should also be noted that the compressive strength in cores and in standard specimens may differ significantly from the compressive resistance of the structure, the latter also being affected by the concrete cracking, different loading rates and confinement effect due to the transverse reinforcement.⁴

As water expands by approximately 9% upon freezing, this causes internal pressure on moist concrete. If the concrete is not frost-resistant, it can be damaged. Frost-resistant concrete can be produced by adding an air-entraining agent to the concrete mixture. Air pores are produced during the concrete mixing, and air-entraining admixture enables the fresh concrete to stabilize. The entrained air voids are capable of absorbing the increased volume of freezing water from the water-filled capillary pores.⁵ Air-entrained concrete is used in cold climate regions for outdoor structures, such as bridges, facades, and balconies.

Comprehensive condition surveys are carried out regularly on Finnish bridges. According to national instructions, concrete strength should be measured using cores in every condition survey.⁶ Thus, it is important that the results of the core tests lead to the correct conclusions on the compressive strength and in some cases even on the conformity of concrete. Extensive attention was paid to assessing the compressive strength of concrete via drilled cores in the late 2010s, when excessively high air content and thus very low values of compressive strength were reported by air-entrained concrete used in some Finnish bridge and deck structures.⁷

Since earlier studies on concrete's core properties were mostly carried out on nonair-entrained concrete, the purpose of this study is to gain further information on air-entrained concrete when determining compressive strength by means of the drilled cores. The studied issues were the size effect of the core specimens, the correlation between the core strength and the same size cylinder specimen strength, the effect of moisture conditions during testing, as well as the correlation between the core strength and the strength obtained from the standard specimens. The tested cores were drilled axially from the 150 × 300 mm cylinder specimen, which means there were no notable differences in the compaction and curing conditions between the core and cylinder specimens. This would have been inevitable if the cores had been taken from the real structure. Because the cores were taken at different heights from the 150 × 300 mm test specimen, this also provided some information on the differences in density and strength values over the cylinder specimen.

2 | THEORETICAL BACKGROUND

Many of the properties of test specimens affect the strength they provide. At least the length-to-diameter ratio, the compressive direction in relation to the casting direction, the effect of the drilling, the size and the moisture content have some influence on the compressive strength of the test specimen.

2.1 | Slenderness effect

Transverse tensile strains are formed in the test specimen as a result of the axial compressive force. Since the tensile strength of concrete is relatively low, these strains have a significant effect on the compression test result of the specimen. The degree of transverse expansion is different between the steel plates of the compression device and the concrete test specimen due to their differences in elastic modulus, Poisson's ratio and surface area. Therefore, friction is formed between the steel plates and the concrete specimen during the compression test. This prevents the transverse expansion of the test specimen. The effect of friction forces on the concrete specimen is lower further away from the end plates. Therefore, the length-to-diameter ratio of the specimen has a clear effect on the compressive strength result.⁸

2.2 | The effect of the compressive direction

Plastic settlement occurs in fresh concrete. This can cause weaker areas under the aggregate particles and rebars due to bleeding water.⁴ If the test specimen is then compressed perpendicular to the casting direction, the weaker zone will be parallel to the principal stress and thus the compressive strength of the test specimen may be lower.⁹

2.3 | Drilling effect

During the core drilling, the diamond drill also cut the aggregate particles, while in molded specimens all aggregate particles are fully surrounded by the cement matrix. The compressive strength obtained from the cores has generally been found to be lower than the compressive strength obtained from the cylinders. One reason for this is that since the cut aggregate particles on the core surface are only partially bonded to the hydrated cement, the effective cross-sectional area of the core is possibly smaller than that of a correspondingly-sized molded

specimen¹⁰ and the cut aggregate particles may pop out of the specimen during compression.¹¹ It has also been suggested that drilling as a destructive method would cause microcracking in the cement matrix and weakening of the bond between the aggregate particles and the hydrated cement.¹² In addition, different compaction methods are used between the structures and the test specimens, which might also influence on the compressive strength.

2.4 | Size effect

Although there is no uniform agreement on the effect of the core size on the compressive strength of concrete, several theories have been put forward for this effect. It has been argued that small cores have weaker compressive strength because the proportion of the drilled and potentially damaged surface to the volume of the core is significantly higher in small cores than larger ones.¹²

According to the classical Weibull¹³ theory, the strength of the specimen would be followed by the weakest part of the specimen. Large specimens are more likely to have weaker areas than small specimens, hence their compressive strength is probably lower. On the other hand, local strength differences in concrete, such as those which have been formed due to concrete segregation, become more apparent in small cores. Tucker¹⁴ proposed another theory based on his experiments on molded specimens. He suggested that the strength obtained from the specimen would be the sum of all parts included in the specimen.

The bending deformation of the loading plates has been also suggested to affect the strength of larger specimens due to the greater splitting effect.¹⁵ Despite this, by following the requirements of the test standards for the load equipment, the effect of this phenomenon can be assumed to be minor.

Bartlett & MacGregor¹¹ reviewed all the above-mentioned theories and compared them with experimental results compiled from several different studies. They concluded that the effect of the drilled surface was most significant theory for the size effect on the compressive strength of concrete.

2.5 | Moisture content

Concrete cores are mostly tested in air-dried moisture condition, while the molded 150 mm cubes and 150 × 300 cylinders are defined to be tested at the saturated condition. The moisture content of the test specimen is widely known to have a significant effect on the compressive strength. A higher moisture content will give

lower compressive strength values.¹ This has partly been explained by the drying shrinkage. As a result of the drying of the hardened cement paste, the surface tension in small pores increases, which makes the cement gel more compact.¹⁶ Another suggestion has been that under compression, the increase in the internal pressure on the water-filled capillary pores causes lower compressive strengths. It has also been suggested that this effect applies only to the fully saturated specimens. On the other hand, due to the deformations caused by the compression, the partially saturated specimen may also become fully saturated during the compression test.¹⁷

3 | CODE PROVISIONS

When compressive strength is assessed in an existing structure, the structure itself limits the possibilities of what kind of specimen can be used – for example, from a densely reinforced structure it is possible to take only relatively small diameter cores. Therefore, there is quite a wide range of possible core properties given in test standards.

Core strength is easily obtained by dividing the ultimate load of the compression test over an average cross-sectional area of the specimen. The difficulty arises when the core strength is converted to that which is comparable with the other types of cores or to match the standard specimen strength, which is after all the value used in design and conformity assessments. Therefore, different conversion factors and equations have been presented for core testing in several codes and national guidelines.

The ACI Guide 214.4R-10¹⁸ provides a procedure to convert the core strength to the equivalent in-place strength, f_c , for considering several factors as follows:

$$f_c = F_{dia} \cdot F_{mc} \cdot F_{l/d} \cdot F_d \cdot f_{core}, \quad (1)$$

where F_{dia} is a factor including the effect of the diameter; F_{mc} is a factor including the effect of the moisture condition; $F_{l/d}$ is a factor including the slenderness contribution; $F_d = 1.06$ is a coefficient including the drilling contribution; and f_{core} is the measured core strength. The definitions of the ACI Guide for these factors and comparison with those in other guidelines and codes are presented below. All factors are presented with the notation style given in the ACI Guide.

3.1 | Size effect

There is a high variation in how different codes and guidelines considered the size effect of the drilled cores.

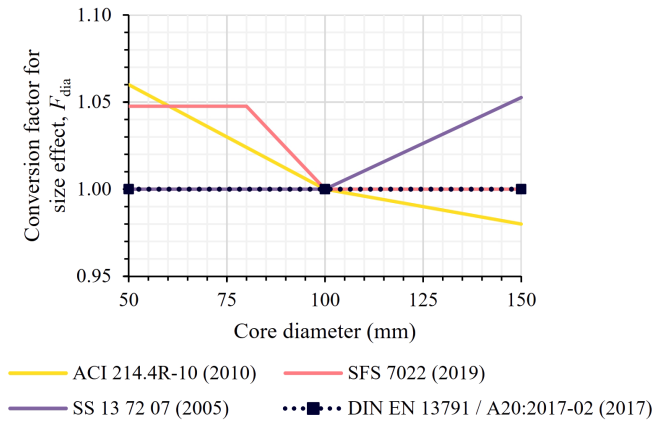


FIGURE 1 Comparison of conversion factors for size effect given in different codes and guides

The factors given in ACI Guide 214.4R-10¹⁸ and Finnish national guideline SFS 7022¹⁹ will increase the compressive strength of small cores. In Sweden²⁰ the compressive strength of large cores are corrected to the higher value, while with cores smaller than 100 mm, compressive strength is not changed. The effect of the correction for the cores with a diameter of more than 100 mm is thus completely different to that given in the ACI Guide 214.4R-10.¹⁸ In German codes, the conversion factors for size effect are not given. DIN EN 13791 / A20:2017-02²¹ assume air-dried 50 mm, 100 mm, and 150 mm cores with a length-to-diameter ratio of 1.0 to correspond to the strength of the soaked 150 mm cube.

The size effect procedures given in the above-mentioned guidelines are summarized in Figure 1. To facilitate the comparison, all factors are presented in the same format as in ACI Guide 214.4R-10¹⁸ and adjusted to have a core with a diameter of 100 mm as a reference case ($F_{dia} = 1.00$).

3.2 | Moisture effect

The moisture content factor in ACI Guide 214.4R-10¹⁸ is $F_{mc} = 1.09$ if the testing of the cores is preceded by 48 hr of water soaking, and $F_{mc} = 0.96$ if testing is preceded by storage for 7 days at a temperature of 16–21°C and below 60% relative humidity. The factor $F_{mc} = 1.00$ is used if the storage of the cores before testing has been in accordance with the ASTM standard C42 (2020), that is, storing in a sealed bag or similar for at least 5 days after moisture exposure caused by the preparation of the specimens. European standards have specified that cores should be tested primarily in an air-dried condition (DIN EN 13791 / A20:2017-02; EN 13791:2019; SS 13 72 07:2005).

3.3 | Slenderness effect

Depending on the code and instruction, it may be desirable for the core strength to end up with the cube strength or with the cylinder strength. The reference case ($F_{l/d} = 1.0$) for the procedure depends on that, hence the reference length-to-diameter ratio is 1.0 or 2.0.

The ACI Guide 214.4R-10 (2010) gives an equation for the effect of the l/d ratio as follows:

$$F_{l/d} = 1 - (\beta - \alpha \cdot f_{core}) \left(2 - \frac{l_{core}}{d_{core}} \right)^2, \quad (2)$$

where β is a factor including the effect of moisture condition ($\beta = 0.117$ if $F_{mc} = 1.09$; $\beta = 0.130$ if $F_{mc} = 1.00$ and $\beta = 0.144$ if $F_{mc} = 0.96$); α is a constant $4.3 \cdot 10^{-4}$ 1/MPa; f_{core} is the measured core strength; l_{core} is a length, and d_{core} is a diameter of the core.

ASTM standard C42 (2020)²² specifies the conversion factors for the cores with length-to-diameter ratios of 1.0–2.0. In the Swedish procedure, the slenderness effect factor is determined from the diagram presented in SS 13 72 07²⁰ for length-to-diameter ratios from 0.5 to 3.0.

In the British national annex for standard BS EN 12054-1 (2009),²³ the length-to-diameter ratio is considered by Equation 3a when converting the core strength to the cylinder strength and by Equation 3b when converting is made to the cube strength. The factors for slenderness effect is no longer provided in the recently revised standard BS EN 12504-1 (2019),²⁴ since the other length-to-diameter than 1.0 and 2.0 has been stated as exceptional there.

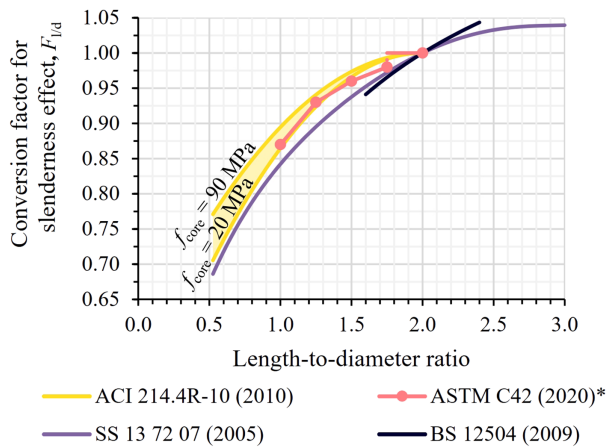
$$F_{l/d} = \frac{2.0}{1.5 + \frac{d_{core}}{l_{core}}} \text{ if } 1.6 \leq \frac{l}{d} \leq 2.4 \text{ (cylinder strength)}. \quad (3a)$$

$$F_{l/d} = \frac{2.5}{1.5 + \frac{d_{core}}{l_{core}}} \text{ if } 1.0 \leq \frac{l}{d} \leq 1.2 \text{ (cube strength)}. \quad (3b)$$

The slenderness factors given in the above-mentioned guidelines are summarized in Figure 2. To facilitate the comparison, all factors are presented in the same format as in ACI Guide 214.4R-10 (2010) and adjusted to have the length-to-diameter ratio of 2.0 as a reference case ($F_{l/d} = 1.00$).

3.4 | Other effects

In addition, a conversion factor to take into account the possibility of the lateral reinforcement in the core has been given in BS EN 12054-1 (2009),²³ and a conversion



*) Different moisture condition of cores (storing in a sealed bag for min. five days).

FIGURE 2 Comparison of slenderness effect for air-dried cores given in different codes and guides

TABLE 1 Mix proportions of the concrete mixes

	Mix 1	Mix 2	Mix 3	Ref mix
Effective water-cementitious ratio	0.40	0.48	0.39	0.52
CEM II/B-M(S-LL) 42.5 N (kg/m ³)	435	375	435	385
Silica fume (kg/m ³)	–	–	15	–
Effective water (l/m ³)	175	180	175	200
Fine aggregate 0/1 mm (kg/m ³)	125	145	95	305
Natural graded 0/8 mm aggregate (kg/m ³)	850	870	860	485
Crushed 0/8 mm aggregate (kg/m ³)	–	–	–	270
Crushed coarse aggregate 6/16 mm (kg/m ³)	740	750	755	710
Air-entraining agent (%) ^a	0.03	0.02	0.02	–
Plasticizing agent (%) ^a	1.09	0.61	1.20	0.62

^aAmount of air entraining agent and plasticizing agent are percentages of the mass of cement.

factor to take into account the weakening effect of the compaction pores when determining the potential strength by means of the drilled cores is given in BS 6089 (2010).²⁵

4 | EXPERIMENTAL PROGRAMME

4.1 | Concrete mixes

The study covered four different concrete mixes. Three of them (Mixes 1–3) were air-entrained concretes, while the

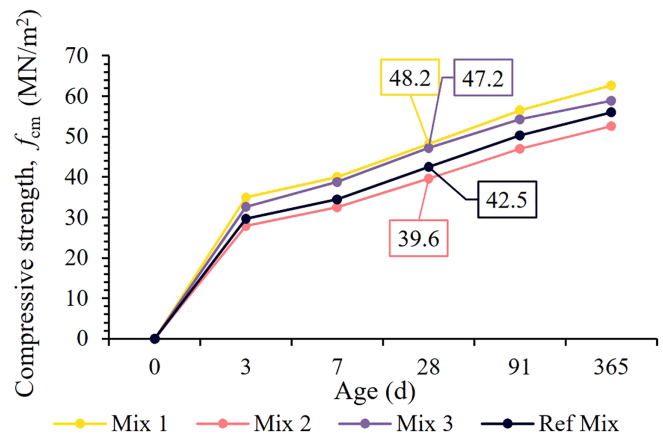


FIGURE 3 Compressive strength development of studied concrete types

fourth mix was a regular nonair-entrained concrete as a reference (Ref Mix). The studied concrete types were selected to correspond to the commonly used concrete types in Finnish infrastructure. The mix proportions for the studied concrete types are presented in Table 1. The maximum aggregate size in all concrete mixes was 16 mm. The crushed aggregate was produced by crushing Finnish bedrock (granite and granodiorite), the strength of which is stated to be remarkably high. The strength development of the studied concrete mixes was examined in accordance with standard EN 12390–3 (2019)²⁶ with six 150 × 300 mm cylinders at five different concrete ages (Figure 3).

4.2 | Casting and preparation of specimens

The specimen types as well as the total number of specimens are shown in Table 3. Due to the high number of specimens, it was necessary to divide a concrete casting of each concrete mix into two batches, which were made on the same day. An equal number of each specimen type were cast in either batch. 150 × 300 mm cylinder specimens were cast in steel molds while the cube specimens were cast in steel and plastic molds – both in equal numbers. All cores were drilled from 150 × 300 mm concrete cylinders cast in plastic molds except for 150 × 300 mm core specimens, which were drilled from 235 × 340 mm cylinders – also cast in plastic molds.

The consistency and the air content tests for the fresh concrete were performed twice for each batch – at the beginning of the casting and after the first half of the specimens were cast. The duration of the first half of the cast was approximately 1 hr. The consistency was determined by the slump test²⁷ and by the flow table test.²⁸

TABLE 2 The results of the fresh concrete tests (at the beginning of the casting/at the midpoint of the casting)

Concrete mixture	Slump test (mm)		Flow table test (mm)		Air content (%)	
	The first batch	The second batch	The first batch	The second batch	The first batch	The second batch
Mix 1	130 / 70	160 / 90	490 / 430	470 / 400	4.1 / 4.2	5.6 / 5.2
Mix 2	180 / 180	160 / 120	530 / 530	520 / 470	3.9 / 5.3	4.4 / 4.9
Mix 3	180 / 200	200 / 190	480 / 490	540 / 480	4.0 / 5.6	3.8 / 5.6
Ref mix	180 / 160	120 / 110	500 / 510	460 / 460	1.8 / 1.9	1.8 / 2.6

TABLE 3 The compressive strength and density test results for each specimen type and concrete mix

Concrete	Specimen	Moisture condition	<i>n</i>	Density		Compressive strength		
				$\bar{\rho}$ (kg/m ³)	<i>s</i> (kg/m ³)	\bar{f}_c (MN/m ²)	<i>s</i> (MN/m ²)	
Mix 1	Core	50 mm × 50 mm	Air-dried	24	2,330	31	65.8	6.4
		80 mm × 80 mm	Air-dried	36	2,330	25	67.0	3.8
		100 mm × 100 mm	Air-dried	24	2,290	20	62.4	3.4
		150 mm × 300 mm	Air-dried	24	2,330	8	53.4	1.7
	Cyl.	100 mm × 100 mm	Air-dried	12	2,330	14	69.8	3.7
		150 mm × 300 mm	Air-dried	12	2,330	19	58.3	2.4
		150 mm × 300 mm	72 h soaked	18	2,340	19	55.2	3.4
Cube	150 mm	Air-dried	12	2,310	7	59.7	3.6	
Mix 2	Core	50 mm × 50 mm	Air-dried	24	2,350	17	53.4	4.4
		80 mm × 80 mm	Air-dried	36	2,330	19	54.6	3.2
		100 mm × 100 mm	Air-dried	24	2,330	13	54.3	2.5
		150 mm × 300 mm	Air-dried	24	2,330	7	43.7	1.3
	Cyl.	100 mm × 100 mm	Air-dried	14	2,360	10	65.2	1.7
		150 mm × 300 mm	Air-dried	12	2,340	10	47.7	1.1
		150 mm × 300 mm	72 h soaked	18	2,340	13	45.5	1.0
Cube	150 mm	Air-dried	12	2,340	11	56.8	2.4	
Mix 3	Core	50 mm × 50 mm	Air-dried	24	2,360	25	66.5	8.0
		80 mm × 80 mm	Air-dried	36	2,350	14	68.1	2.2
		100 mm × 100 mm	Air-dried	24	2,350	8	65.0	2.3
		150 mm × 300 mm	Air-dried	24	2,330	5	47.1	1.0
	Cyl.	100 mm × 100 mm	Air-dried	14	2,360	11	72.7	2.3
		150 mm × 300 mm	Air-dried	12	2,340	12	50.8	0.7
		150 mm × 300 mm	72 h soaked	18	2,330	12	48.3	1.6
Cube	150 mm	Air-dried	12	2,350	7	64.8	2.7	
Ref mix	Core	50 mm × 50 mm	Air-dried	24	2,360	15	66.4	5.9
		80 mm × 80 mm	Air-dried	36	2,360	9	62.8	4.6
		100 mm × 100 mm	Air-dried	24	2,350	6	62.6	4.3
		150 mm × 300 mm	Air-dried	24	2,350	4	46.2	3.3
	Cyl.	100 mm × 100 mm	Air-dried	14	2,390	8	70.1	3.5
		150 mm × 300 mm	Air-dried	12	2,360	5	50.4	3.5
		150 mm × 300 mm	72 h soaked	18	2,370	10	47.5	3.8
Cube	150 mm	Air-dried	12	2,370	7	63.0	4.1	



FIGURE 4 The different stages of the experimental programme: compaction (a), storing (b), drilling (c) and testing (d)

The air content of the concrete was determined by the water column method according to EN 12350-7 (2019).²⁹ The results in Table 2 show that concrete slowly stiffens during the casting, but for Mix 1 there was a significant difference between these two measurements.

For practical reasons, all specimens were cast on one layer. The compaction of concrete was carried out with a vibrating table according to standard EN 12390-2 (2019)³⁰ (Figure 4a). The molds were covered with a plastic film for 46 to 50 hr before demoulding, followed by soaking in the water tanks until the age of 28 days. The temperature of the water tanks varied between 18 to 22°C during the curing. Specimens were then stored in laboratory conditions at temperatures of 19 to 22°C and an of average 60% relative humidity until testing (Figure 4b).

The core specimens were drilled with the water-cooled diamond core drill bits (Figure 4c). Drilling was made parallel to the casting direction and centrally through a 150 × 300 mm cylinder. Several core specimens were taken from the cylinder as shown in Figure 5. The cores were cut using a water-cooled diamond saw and both ends of the cores were grinded to meet the requirements of standard EN 12390-1

(2012).³¹ Compression tests were made at the age of 3 months in accordance with EN 12390-3 (2019)²⁶ and EN 12504-1 (2019)³² (Figure 4d).

Local density differences were examined from two 150 × 300 mm cylinders for each concrete mix from three height locations. Perpendicularly drilled cores of 50 mm in diameter were cut into five specimens, as shown in Figure 6. The density was determined from these water-saturated specimens by dividing their mass by its volume as determined by the water-displacement method.³³ The samples were combined to give a density result from three different depths from each height location.

5 | RESULTS AND DISCUSSION

The mean and SD values of compressive strengths and densities are presented in Table 3. The strength results are obtained directly as a quotient of the ultimate load divided by the cross-sectional area, without any conversion factors.

Figure 7 shows the relationship between the average strength obtained from each specimen type to the soaked 150 × 300 mm cylinder's average strength. The widely

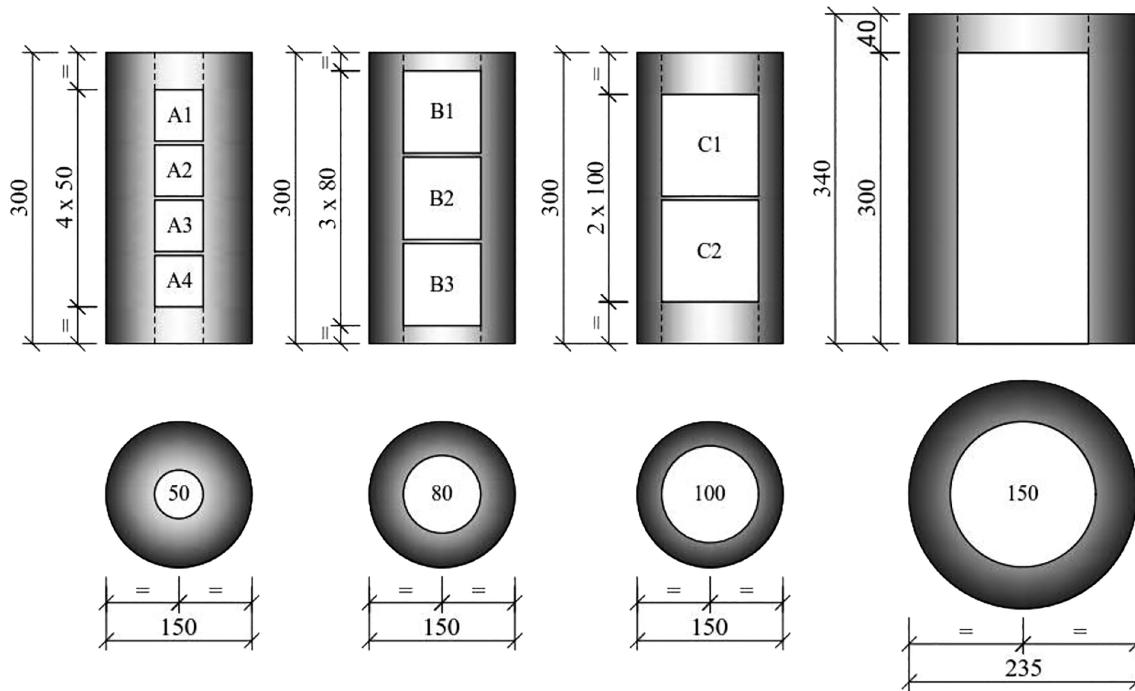


FIGURE 5 Core sampling from the concrete cylinders

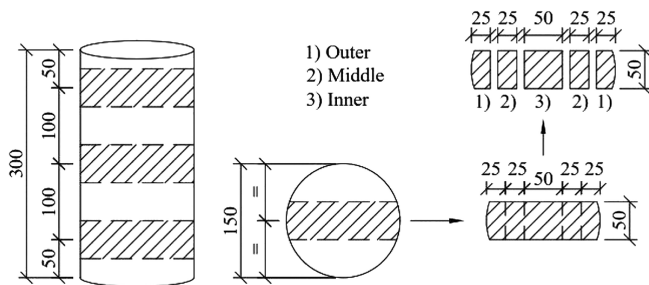


FIGURE 6 The location of density specimens on concrete cylinders

known^{34,35} slenderness effect is clearly seen in the test results. The strength values obtained from 150×300 mm cylinders are at a distinctly lower level than strength values obtained from test specimens with a length to diameter ratio of 1.0.

5.1 | Size effect

The compressive strength ratios between 100×100 mm and 50×50 mm cores and ratios between 100×100 mm and 80×80 mm cores are shown in Figure 8. Combining the results of all concrete types, the compressive strength of 100×100 mm cores was on average 3% lower than the compressive strength of 50×50 mm and 80×80 mm cores. However, it should be noted that there were significant differences in the ratio between the different concrete

types. Depending on the concrete type, the difference varied from -7% to $+2\%$. This also gives some indications that the significance of the size effect would be dependent on the concrete type. There was no consistent difference in the significance of the size effect between the air-entrained concrete and the reference concrete.

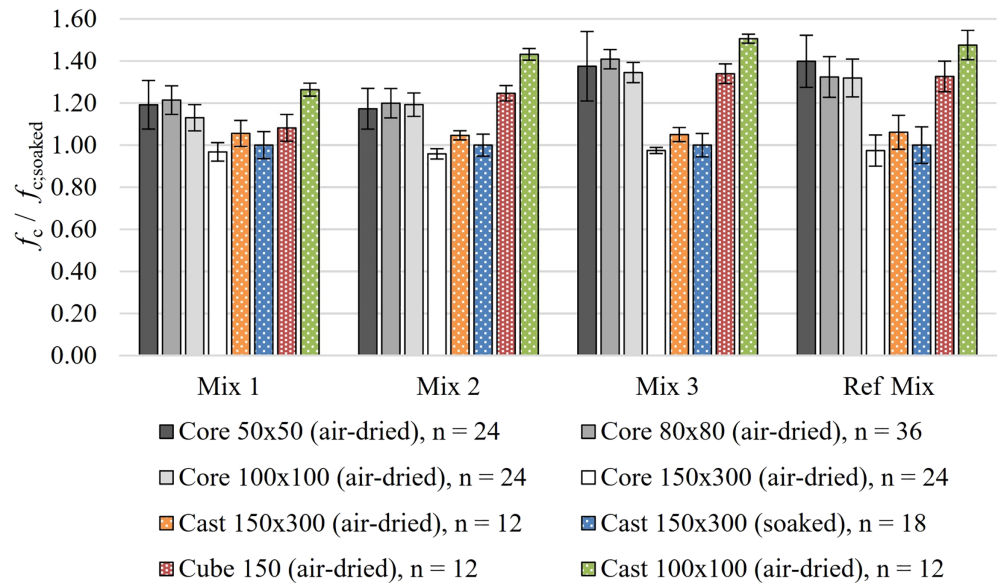
In this study, the core diameter impact on the compressive strength was observed to be quite different to that in several other studies. Many researchers have observed the increase in compression strength with the larger core diameters.^{11,36,37} At the same time there are plenty of studies with no size effect observed.^{38,39}

The results also showed a widely-known phenomenon^{37,39} of increased deviation in the results as the size of the specimen decreased. The coefficient of variation determined from the results of Table 3 was 10% for 50×50 mm core while it was 5% for 80×80 mm and 100×100 mm cores. It is also worth mentioning that a 50 mm diameter, which was used in some of the cores studied is smaller than the minimum requirement given in EN 12390-1 (2012),³¹ where the lower limit for the diameter is three and a half times the maximum aggregate size.

5.2 | Core strength related to the standard specimen strength

The ratios between the average core, cylinder and cube strengths are shown in Figure 8. When including all tested

FIGURE 7 The comparison of average compressive strength and standard deviation of each specimen type to the compressive strength average obtained from the soaked 150×300 mm cylinders



concrete mixes, the strength ratio of 100×100 mm cores and air-cured 150×300 mm cylinders was on average 0.85, while the ratio was 0.81 between 100×100 mm cores and soaked 150×300 mm cylinders. These ratios are of the same order as the conversion factor 0.82 between 1.0 and 2.0 length-to-diameter ratios presented in EN13791 (2019).⁴⁰ However, there were significant differences in the above-mentioned ratios depending on the concrete type. The ratio between the 100 mm core strength and the air-cured 150×300 mm cylinder strength varied from 0.78 to 0.93 depending on the concrete type, while the ratio between the 100 mm core strength and the soaked 150×300 mm cylinder strength varied from 0.74 to 0.88.

Since the mix proportions between Mix 1 and Mix 3 were almost equal except for the silica fume, which was included in Mix 3, the results give some indications that the use of the silica fume might have an advantageous effect on the compressive strength in test specimens, with the length-to-diameter ratio of 1.0 compared with the strength of the specimens with a l/d -ratio of 2.0. One explanation for this phenomenon could be possible differences in the effect of silica on the compressive and splitting tensile strength properties of concrete. This has been referred to, for example, in the results of the studies by Amudhavalli & Mathew⁴¹ and Jaber, Gorgis & Hassan.⁴² The splitting tensile strength value could be expected to be of greater importance in the compressive strength tests of slender specimens due to the lesser effect of the end friction.

The strength ratio between 100×100 mm cores and air-cured 150 mm cubes was on average 1.01 for all concrete mixes, while the strength ratio of air-cured 150×300 mm cylinders and 150 mm cubes was on average 0.85, which agreed with the ratios 0.82–0.85 reported by Zabihi & Eren.⁴³ There were also clear differences

between different concrete types in the above-mentioned ratios. It is noteworthy here that cubes are the only specimen type in this study, which was tested perpendicular to the casting direction. Therefore, when comparing the strength obtained from other specimens with the cube strength, the effect of the testing direction is also included in the test results. It is more significant in concrete types, which are more sensitive to segregation.

5.3 | Drilling effect

The ratios between cylinder strength and core specimen strength are shown in Figure 8 for 100×100 mm and 150×300 mm specimens. The curing, compaction and storing of test specimens as well as moisture conditions during the compression test were similar between cylinder specimens and cores. Thus, the difference in the strength between them is mainly caused by the different surfaces of the specimens. Based on the test results, drilling seems to have a clear weakening effect on the compressive strength. Similar findings have been achieved in several other studies.^{36,44,45} In the current investigation, drilling had more of an effect on compressive strength for 100×100 mm specimens than for 150×300 mm specimens. This may be due in part to the smaller size of the specimen, which results in the ratio of the drilled surface area to the specimen volume being much bigger on the 100×100 mm specimen than the 150×300 mm specimen. A difference in slenderness might also have an influence.

Compressive strength of the 150×300 mm cores was on average 7%–8% lower than the strength of the cylinder specimens of the same size, while with the most common

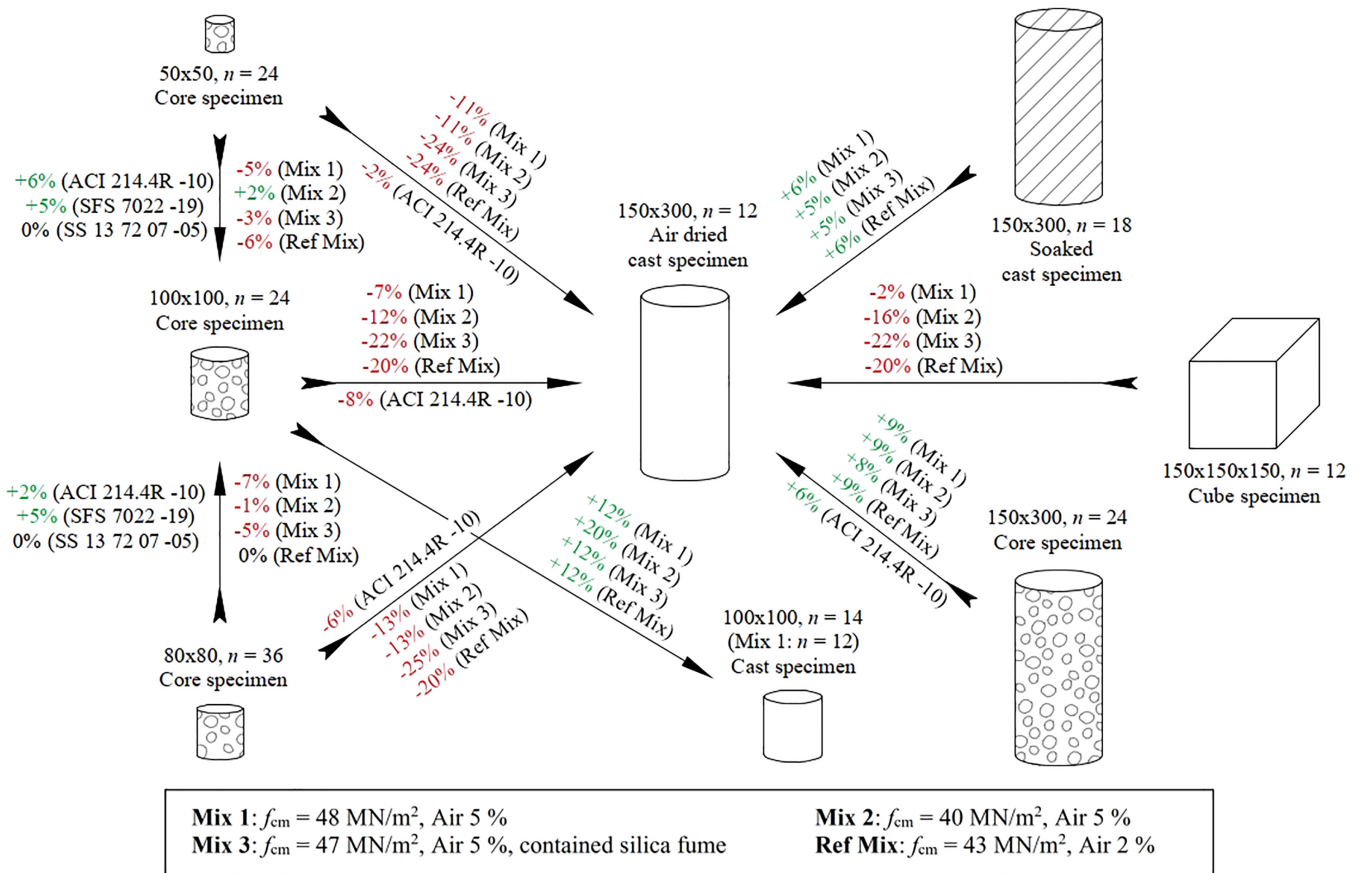


FIGURE 8 Ratios of compressive strength mean values obtained from different specimen types and comparison to the ratios provided by the different codes

core specimen size – $100 \times 100 \text{ mm}$ – that ratio was 11% excluding Mix 2, which had a 17% ratio. These ratios are higher than the correction factors for the drilling effect proposed by Bartlett & MacGregor.⁴⁶

Based on the results, the effect of drilling on air-entrained concrete did not differ from that of nonair-entrained concrete, and the magnitude of the drilling effect seems to be independent of the concrete mix. Bisher⁴⁷ had previously observed that concrete age, the amount of cement or the type of aggregate did not have significant influence on drilling effect.

5.4 | Effect of the moisture content during compression test

The effect of the specimen moisture content during testing was studied by comparing the compressive strength values of 72 hr-soaked and air-dried $150 \times 300 \text{ mm}$ cylinder specimens. Figure 8 reveals that the compressive strength average of the air-dried $150 \times 300 \text{ mm}$ cylinders was 5%–6% higher than that of the same sized 72 hr-soaked test specimens. The ratio seems to be independent of the concrete mix and there was no significant

difference observed between the air-entrained concrete types and the reference concrete.

The observed difference is slightly higher than that in Li's⁴⁸ study of 0.45 water/cement ratio concrete (4%), but is considerably lower than the difference in 0.65 water/cement ratio concrete (16%). It is noteworthy that Li used smaller $100 \times 200 \text{ mm}$ cylinder specimens in his study, so the saturation rate can be assumed to be higher.

The differences in the compressive strength between soaked and air-dried cores in various studies are significantly higher than those obtained for the cylinder specimens in this study. Bartlett & MacGregor⁴⁹ put together data from several different studies and concluded that the strength obtained from air-dried cores was on average 14% higher than the strength obtained from the cores that had been soaked for at least 40 hr. Khoury et al.³⁴ came to a very similar conclusion in their recent study.

5.5 | Strength and density differences in test specimens

Differences in density and compressive strength values in different parts of $150 \times 300 \text{ mm}$ cylinders were clarified by

comparing the results of the core specimens taken from different height positions. In addition, differences in density in the transverse direction of the cylinder were studied.

It can be seen from Figure 9 that the compressive strength increased in most test specimens from the casting surface to the bottom. This finding is in agreement with the findings of Moccia et al. (2020).⁵⁰ A similar phenomenon is also seen in density results in Figure 9, but with the difference that the cores taken closest to the casting surface in many cases have a higher density than the next core below. Results also show that with the reference mix, the density is almost independent of the height position. This indicates that the entrained air voids may not be evenly distributed in air-entrained concrete mixes. The results of the horizontal density differences at different height positions are shown in Figure 10.

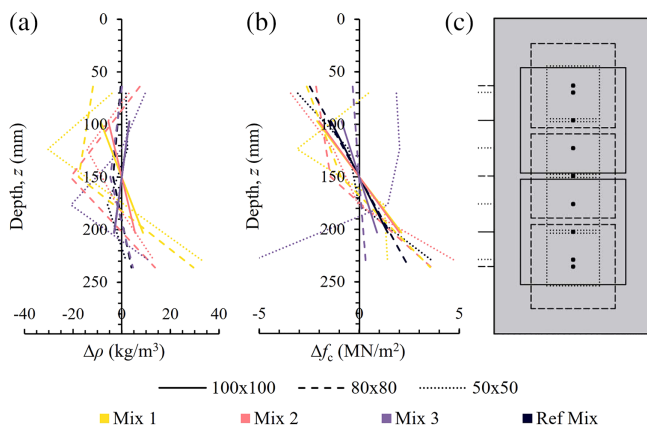


FIGURE 9 The comparison of average density (a) and average compressive strength (b) at different height locations (c) of each specimen type to the total average values obtained from the same size cores

6 | CONCLUSIONS

This paper presents the compressive strength results obtained from different types of concrete specimens with similar compaction and curing conditions. The influence of the size of the core specimens, the correlation between the core strength and the same size cylinder specimen strength, the effect of the moisture condition during testing, as well as the correlation between the core strength and the strength obtained from the standard specimens were studied with more than 650 test specimens made with four different concrete types. The conclusions of this study can be presented as follows:

1. The influence of the specimen size on the concrete compressive strength with drilled cores as well as the correlation between core strength and standard specimen strength is dependent on the concrete mix. It is recommended that a similar study with a larger number of different concrete mixes be conducted in order to determine the effect of the different components and properties of the concrete on the strength ratios between different specimen types.
2. Drilling has a clear weakening effect on the compressive strength of the test specimen. Based on the test results, the authors propose a multiplying factor of 1.09 for 150 × 300 mm core size and a factor of 1.12 for 100 × 100 mm core size for concrete types with maximum aggregate size of $D_{max} = 16$ mm if the compressive strength obtained from the cores is needed to convert to a compressive strength that corresponds of the same sized cylinders under similar moisture conditions. Air-entrained concrete does not seem to differ in terms of drilling effect from the

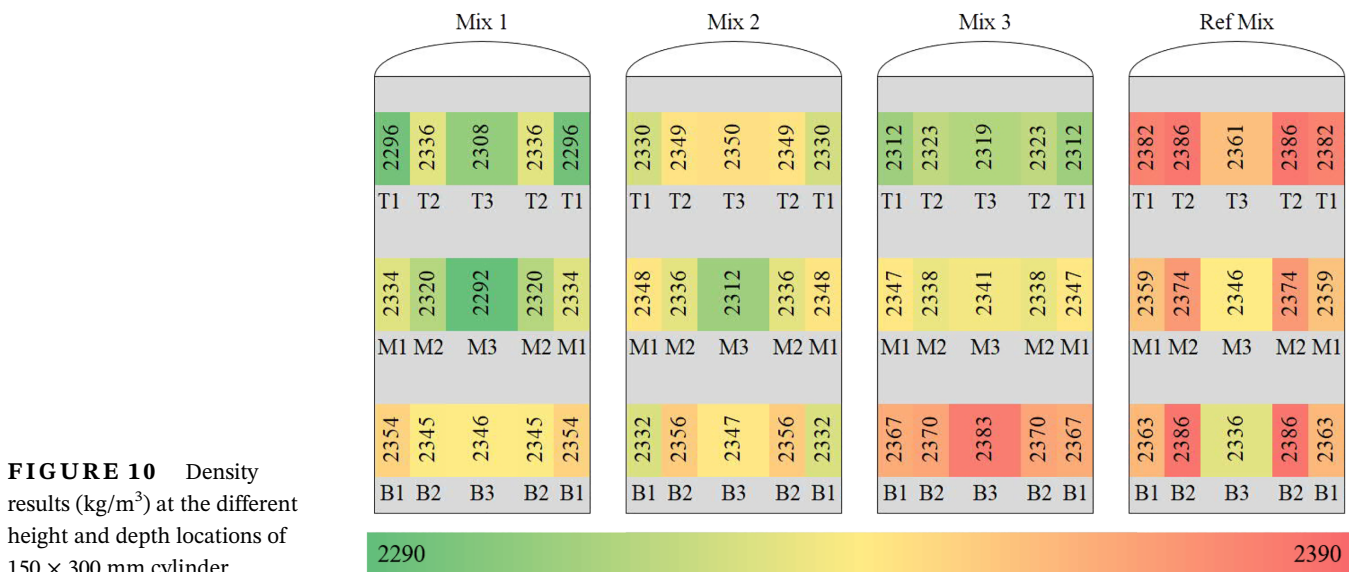


FIGURE 10 Density results (kg/m^3) at the different height and depth locations of 150 × 300 mm cylinder

nonair-entrained concrete. Further tests are required to estimate the drilling effect for concrete types with maximum aggregate sizes different to those used in this study.

3. The compressive strength of the air-dried 150 × 300 mm cylinders was found to be on average 5%–6% higher than the compressive strength of the same size cylinders with a 72 hr soaking period prior to the testing, regardless of the concrete mixes.
4. The SD of the compressive strength results obtained from 50 × 50 mm cores was clearly higher than in other core sizes. The authors propose avoiding the 50 × 50 mm core size for determining the compressive strength of concrete with maximum aggregate size of $D_{\max} = 16$ mm, or alternatively to use a significantly larger number of specimens.
5. The effect of the silica fume was not within the scope of this study, but the results give some indications that the use of silica fume might have an advantageous effect on specimens with a l/d-ratio of 1.0 when compressive strength is compared with specimens with a l/d-ratio of 2.0. The effect of the cement replacement materials on the compressive strength ratios between different specimen types will require further investigation.

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

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SUPPORTING INFORMATION

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