

DEFINING CONCRETE STRENGTH USING SMALLER DIAMETER CONCRETE CORES DURING STRUCTURAL SAFETY EVALUATIONS

ODREĐIVANJE ČVRSTOĆE BETONA PRIMENOM BETONSKIH JEZGARA MANJIH PREČNIKA RADI PROCENE INTEGRITETA KONSTRUKCIJE

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Keywords

- existing structure
- concrete strength
- destructive test
- core extraction
- smaller diameter core
- finite element analysis

Abstract

Weakening of concrete is largely affected by the design of the structures, construction procedure and activities of the construction site, and the length of experiences the structure is exposed to during its service life. However, proper maintenance and timely inspection of existing building can minimize the possible structural failures. The concrete strength of an existing building plays a vital role in overall performance of the building. The estimation of strength properties of concrete can be performed by several methods: visual, destructive and non-destructive test methods. The core test (destructive) is considered as the most reliable test method since it provides the direct compressive strength of the concrete, but often it is difficult of extracting large diameter concrete core due to the presence and interference of reinforcement bars inside of concrete. Therefore, the core diameter varies significantly, even in the same building, in order to extract the cores without interfering the inside main reinforcements. In this study, six existing buildings are studied in the field to estimate the in-situ concrete strength using extracted core test. Different sizes of cores are collected and tested in the laboratory to investigate concrete strength. No consistent trend is found from the collected samples. In these type of cases, more core samples with a smaller diameter (51 mm) might be an option to estimate the existing concrete strength of a building with more consistent manner, and as well as safe for the building during the safety evaluation. To justify the effectiveness of smaller diameter cores, the concrete strength is calculated for different core diameters using finite element analysis in Abaqus environment. Variation in core diameter does not show any significant deviation in estimating concrete strength, which is a promising indication of using cores with 51 mm (2 in.) diameter to estimate existing concrete strength.

Ključne reči

- realne konstrukcije
- čvrstoća betona
- ispitivanje sa razaranjem
- uzorkovanje betonskog jezgra
- jezgra manjeg prečnika
- analiza metodom konačnih elemenata

Izvod

Na slabljenje betona u većoj meri utiče dizajn konstrukcije, postupak izgradnje i aktivnosti na lokaciji za izgradnju, kao i vreme izloženosti konstrukcije elementima tokom radnog veka. Međutim, pravilno održavanje i pravovremena kontrola realnih građevina može minimizirati moguće otkaze konstrukcije. Čvrstoća betona realne građevine igra važnu ulogu u njenoj sveobuhvatnoj nosivosti i radnom veku. Procena osobina čvrstoće betona se može izvesti primenom nekoliko metoda: vizuelno, ispitivanjima sa i bez razaranja. Ispitivanje jezgra (sa razaranjem) se smatra za najpouzdaniju metodu ispitivanja, jer se dobija neposredni podatak o čvrstoći na pritisak betona, ali je često otežano uzimanje uzoraka jezgra betona većih prečnika zbog postojanja armature. Shodno tim, izbor prečnika jezgra se menja u širokim granicama, čak i na istoj građevini kako bi se izbegao uticaj spomenutih ojačanja. U ovom istraživanju, proučavali smo šest postojećih građevina na terenu, kako bismo procenili realnu čvrstoću betona primenom ispitivanja uzoraka betonskih jezgara. Uzorci jezgara različitih veličina su uzeti i ispitivani u laboratorijskim uslovima radi istraživanja čvrstoće betona. Dobijeni rezultati ne ukazuju na neki postojeći trend u ponašanju ove osobine. Kod ovakvog tipa slučaja, veći broj uzoraka manjih prečnika (51 mm) bi odgovarao kao optimalan izbor za konzistentniju procenu preostale čvrstoće betona u datoj građevini, a istovremeno i bezbedniji za samu građevinu u oceni sigurnosti. Opravdanost efikasnosti jezgara manjih prečnika je dokazana primenom analize metodom konačnih elemenata u okruženju Abaqus za proračun čvrstoće betona. Variranje prečnika jezgra nije pokazalo neka značajnija odstupanja u proceni čvrstoće betona, što je činjenica koja obećava upotrebu jezgara prečnika 51 mm (2 ") za procenu preostale čvrstoće betona.

INTRODUCTION

It is often necessary to investigate the concrete strength of existing buildings to determine whether the concrete is in appropriate strength for its designed use. To test the concrete strength of existing buildings, both destructive and non-destructive tests are available for the engineers. The important buildings (such as industrial buildings, schools, hospitals, etc.) should be under close structural health monitoring, and safety evaluations need to be performed in a rigorous and protected manner. Otherwise, terrible accident may take place due to the structural failure of the building which can cost a lot of lives and money.

The tests available for identifying concrete strength range from completely non-destructive tests (no damage to the concrete) through those where the concrete surface is slightly damaged, to partially destructive tests (core tests and pull-out and pull-off tests). The most conventional method of determining in-situ strength of concrete is to extract and test the cores [1-11]. Also, cementing or concrete strength can be found from extracted cores [12-14]. Although the method consists of expensive and time-consuming operations, cores give reliable and useful results since they are mechanically tested to destruction [2]. However, the test results should be carefully interpreted because core strengths are affected by many factors such as diameter, core height to diameter ratio and moisture condition of the core specimen, the direction of drilling, presence of reinforcement steel bars in the specimen and even the strength level of the concrete [7-11, 15]. As per ASTM C 42/C 42M-16, the considerable minimum core diameter is three times the nominal maximum size of the coarse aggregate, but it should be at least two times the nominal maximum size of the coarse aggregate. According to the experimental results obtained, it could generally be stated that core size does not significantly affect the correction factor for a given height-to-diameter ratio [17]. But, it is also found that the compressive strengths of nominal 51 mm (2 in.) diameter cores are known to be somewhat lower and more variable than those of nominal 4 in. (101 mm) diameter cores (ASTM C 42/C 42M-04 [16]). Moreover, smaller diameter cores seem to be more sensitive to the effect of the length-diameter ratio [8]. But, in order to extract the bigger diameter concrete (only) core in the field is sometimes impossible due to the presence of inside reinforcement bars, and affect the strength of structural members during drilling [18]. Usually, the structural members are thoroughly scanned to identify the location of inside reinforcement bars through ferro scanning machine before concrete core extraction from any structural member. In order to achieve desired results, only concrete cores are extracted between two consecutive inside reinforcement bars. To gain enough clearance between the two consecutive reinforcement bars (usually small spaces are found between the two consecutive reinforcement bars in most of the cases), small diameter cores can be a better and easier alternative to extract. And, smaller cores may allow extracting multiple cores from the important structural members without creating any major structural damage. More concrete samples are always better to predict accurate concrete strength. Improved and sophis-

ticated machines make the core extraction easier and less troublesome in handling. In this procedure, small diameter core extraction permits the engineers to stick with their original plan of core extraction.

In this study, six existing buildings are selected to investigate the in-situ concrete strength. Existing strength of concrete is estimated using core extraction (destructive) method. Multiple core samples with different heights and diameters are collected from each building. Equivalent concrete strength can be obtained based on ACI 562-16 [19].

But, conflicting experimental evidence is found concerning the strength of cores with different diameters (ACI 214, 2010, [20]). Therefore, in this paper, the effect of core diameter is presented using finite element analyses in Abaqus environment. Also, based on the finite element analysis, it is proposed that the smaller diameter (51 mm) cores can be used as an effective and trust-worthy alternative to estimate accurate concrete strength.

FIELD DATA COLLECTION

Description of existing buildings and data analysis

In the candidate buildings, both brick and stone aggregate concrete are considered. The description of the buildings (concrete type, age, design concrete strength) is shown in Table 1. For core test, multiple sample data are collected from each building and converted according to the strength correction factor which is shown in Table 6.2 of ACI 214 (2010), [20]. Different core diameters (d) and heights (h) are considered during sample collections. This is the usual case during core sample collections. Typically, field engineers start with bigger diameter cores, and need to switch later on to smaller diameter cores due to the limited access between the inside reinforcement bars. This procedure brings irregularity in core collection which may affect predicting the concrete strength ultimately. However, equivalent in-situ concrete strengths (ACI 562-16, [19]) for extracted concrete cores are determined by Eq.(1):

$$f_{ceq} = 0.9 \bar{f}_c \left[1 - 1.28 \sqrt{\frac{(k_c V)^2}{n} + 0.0015} \right] \quad (1)$$

where: $\bar{f}_c$ is the average concrete strength; V is the coefficient of variation of the strengths; n is the number of samples taken; k_c is the coefficient of variation modification factor.

Table 1. Description of the observed buildings.

Building name	Bldg- A	Bldg- D	Bldg- D	Bldg- B	Bldg- B	Bldg- C
Age (years)	46	19	6	11	11	7
Aggregate type	Brick	Brick	Brick	Stone	Stone	Stone
Design concrete strength (MPa)	17.2	17.2	17.2	24.1	24.1	24.1

Concrete strength from extracted core test

In the core extraction method, a core specimen should be extracted perpendicular to the surface of the concrete as originally placed (as shown in Fig. 1). At least five core

samples are collected from different structural elements (column and beam) of each building for laboratory compressive strength test.

Building-A (brick aggregate concrete), the oldest (46 year-old) building among the candidate buildings, shows the lowest concrete strength among all inspected buildings, as shown in Fig. 2. Eight sample data are taken from different locations (3 data from the beams and 5 data from the columns) of the building, and arranged from the lowest to the highest h/d values. The core diameter is 69 mm, but the heights of the cores are varied. The h/d ratio is kept more

than 1.5 for all collected samples. The calculated equivalent strength, based on Eq.(1), is 8.5 MPa (1226 psi) for the all collected data. No significant trend is found to present the effect of variation of h/d ratio.

In Fig. 3, a diameter of 46 mm is considered during core extraction for building B (19 years old). The sample data are arranged in the ascending of h/d values. The concrete of building B is constructed using brick aggregate. The equivalent strength, based on Eq.(1), for building B is 19.3 MPa (2803 psi).



Figure 1. Concrete core extraction test.

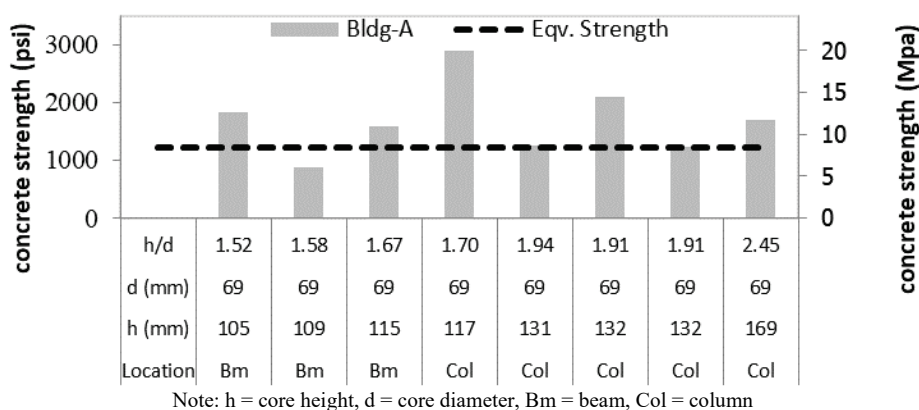


Figure 1. Core test result: concrete strength of Building-A (brick aggregate concrete).

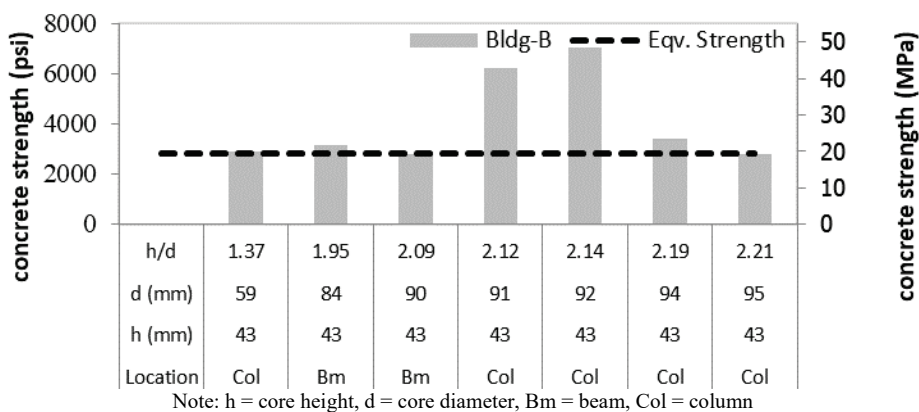


Figure 2. Core test result: concrete strength of Building-B (brick aggregate concrete).

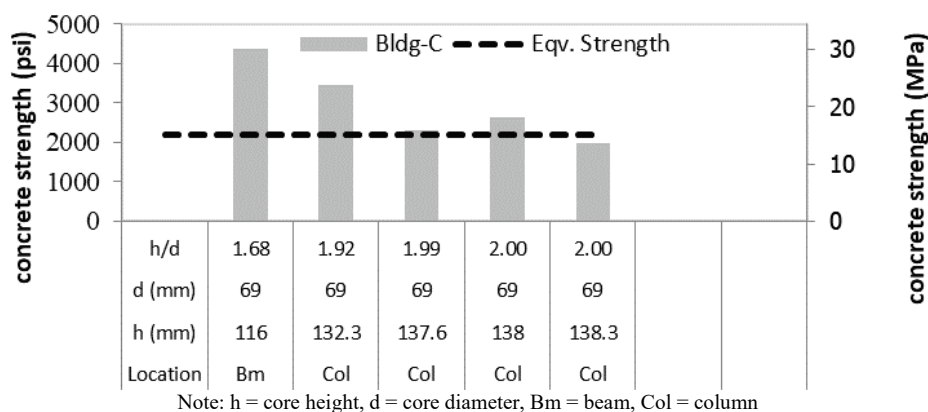


Figure 3. Core test result: concrete strength of Building -C (brick aggregate concrete).

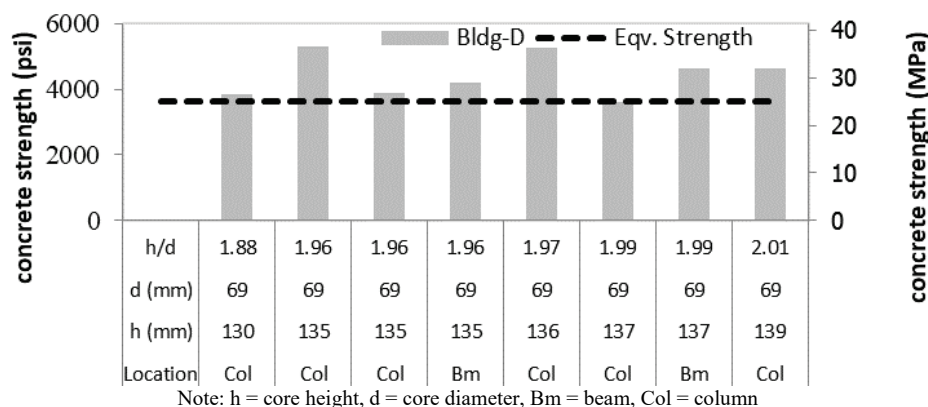


Figure 4. Core test result: concrete strength of Building -D (stone aggregate concrete).

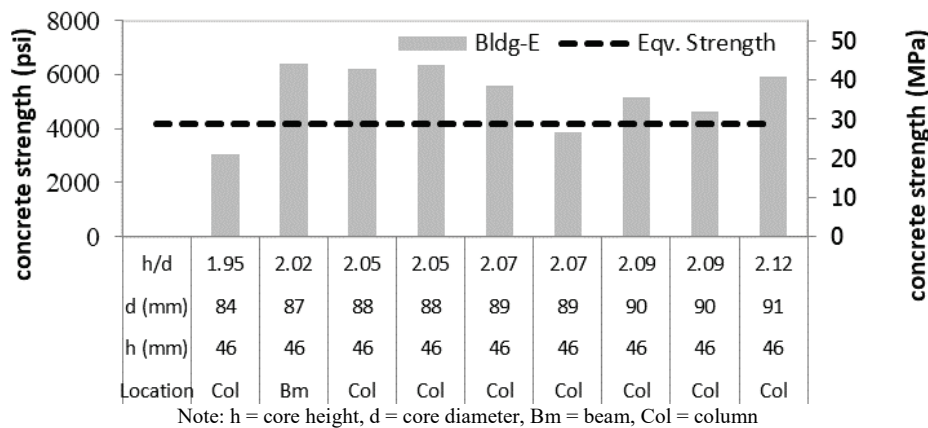


Figure 5. Core test result: concrete strength of Building -E (stone aggregate concrete).

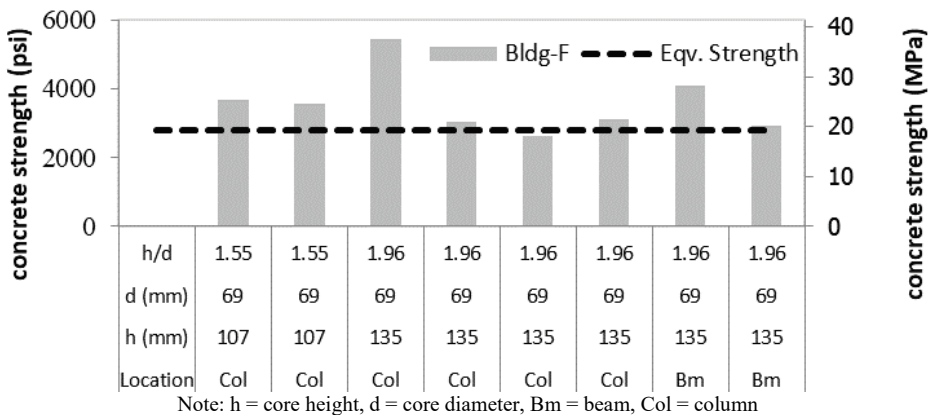


Figure 6. Core test result: concrete strength of Building -F (Stone aggregate concrete).

In the case of building-C (brick aggregate concrete), the Fig. 4 shows 5 sample data (1 data from the beam and 4 data from the columns) for the building which is 6 years old. The extracted concrete cores are 69 mm in diameter. A decreasing trend is found with the increase of h/d ratio for building D. The equivalent concrete strength, based on Eq.(1), is 15.2 MPa (2197 psi).

In Fig. 5, eight data (2 data from the beams and 6 data from the column) are collected and presented for building-D. The building is 11 years old and the concrete is stone aggregate concrete. The data are arranged in the graph in an ascending order of h/d values. The diameter is 69 mm for all the cores. The h/d ratio for all the cores is close to 2.0. The monitored sample data showed a similar and good strength of concrete. The calculated equivalent strength, based on Eq.(1), of concrete is 25 MPa (3637 psi).

In Fig. 6, a diameter of 46 mm is considered during core extraction for building- E (9 years old). Collected sample data are organised in ascending of h/d values. Concrete is made for building E using stone aggregate. The equivalent strength, based on Eq.(1), for build. E is 28.8 MPa (4173 psi).

In the case of building- F (stone aggregate concrete), the Fig. 7 shows 8 sample data (2 data from the beams and 6 data from the columns) for the 7 year old building. The concrete cores are extracted with 69 mm diameter. It can be seen from Fig. 7, there is almost a decreasing trend of concrete strength with the increase of h/d ratio. The equivalent concrete strength, based on Eq.(1), is 19.2 MPa (2778 psi).

Based on the field collected data, no significant trend is obtained depending on diameter variations of cores. This phenomenon might have happened due to the multiple locations of core collection. Also, staged construction is a very common matter in building construction. Time of construction for different stages may vary significantly. Therefore, it is never enough to collect five or six cores to predict the existing concrete strength for the whole building. In this way, it is difficult to define the best predicting core diameter. This phenomenon indicates to collect more core samples with uniform diameter and height.

Comparison of the equivalent concrete strength

In order to draw a precise picture of equivalent strengths with respect to building age and aggregate type, a comparison of equivalent strengths is shown in Fig. 8. In this comparison, buildings C and F are considered as the controls respectively for stone and brick aggregate concrete, since these buildings experienced less service life. In case of brick aggregate concrete, the equivalent core strength (15.2 MPa) of building C shows 12.1 % less strength than the design strength (17.2 MPa) of concrete (brick) of existing building. The equivalent core strength (19.2 MPa) of building F shows 20.6 % less strength than the design strength (24.1 MPa) of concrete (stone) of existing building.

In case of building- A, the equivalent core strength (8.5 MPa) shows 50.6 % smaller strength than the design strength (17.2 MPa) of concrete (brick). Also, this building showed smallest concrete strength which might be because of the age (46 years old) of the building. Now, comparing with the control building (building C), building A shows 44.1 % smaller concrete strength.

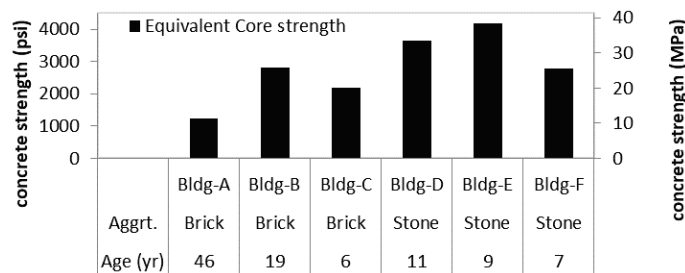


Figure 7. Comparison of equivalent strengths among different buildings.

For building B, the equivalent core strength (19.3 MPa) shows 12.2 % and 26.9 % higher concrete strength than the design strength of building (brick aggregate concrete: 17.2 MPa) and the control building (C), respectively. This equivalent strength is not acceptable if the weakening of concrete over time is considered. Retrofitting design considering on this existing concrete strength would not be a correct decision. More samples are required in order to investigate the approximate accurate strength.

For building- D, the equivalent core test (25.1 MPa) shows 4.2 % and 30.7 % larger strength than the design strength (24.1 MPa) of concrete (stone) and the control building (F), respectively. Again, more core samples are required to investigate the existing strength of concrete.

For building E, core extraction tests are performed to estimate the in-situ concrete strength. The equivalent core tests show 19.5 % and 50.0 % higher concrete strength (28.8 MPa) than the design strength of building E (stone aggregate concrete: 24.1 MPa) and the strength of control building (F), respectively.

Based on Fig. 8, a consistent trend is found in predicting approximate concrete strength among the buildings regardless of core diameter. Older buildings and core with brick aggregate exhibit lesser existing concrete strength. However, the concrete strength of the existing building (especially buildings from the 1980's to 2000's) depends on the time of staged construction (sometimes structural members (roof, beam, column, etc.) of the buildings are constructed in different years), construction procedure, concrete mix design, etc.

Nearly accurate concrete strength can be predicted by collecting more core samples from buildings. Sometimes historically important buildings need rigorous safety evaluation. Equivalent concrete strength based on five to seven cores may not be appropriate. In some cases, critical structural members demand multiple core samples to evaluate the concrete strength, where bigger diameter cores may not be the right option. Another reason of switching to the smaller diameter core is to make core extraction easier. Typically, enough spacing between the two main inside rebars cannot be found to extract concrete (only) cores as shown in Fig. 9. Because of this interruption reason, it is intentionally or unintentionally required to extract the core including main rebar which cannot estimate exact concrete strength, and may bring a negative impact to the structural member. In this study it is suggested to extract small diameter cores to estimate concrete strength since these are easier to drill, handle and store compared to larger diameter cores.

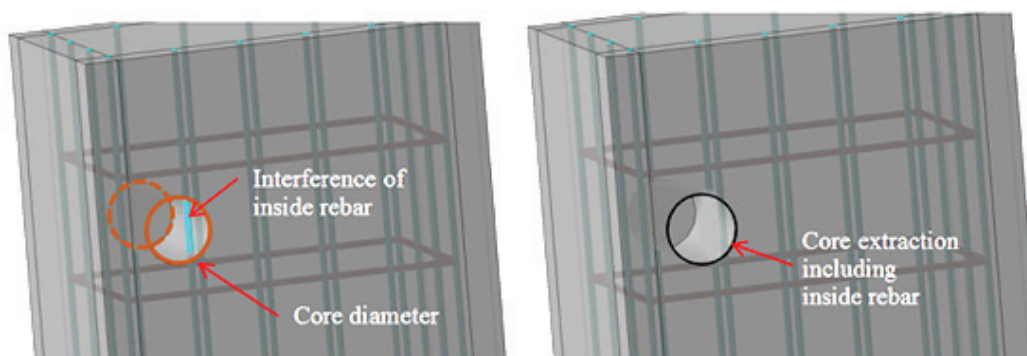


Figure 8. Core extraction including main rebar due to insufficient spacing between two main rebars.

EFFECT OF CORE DIAMETER

To establish the concept of assessing concrete strength using small diameter core, a detailed parametric study is performed using Abaqus 6.13. In this procedure, possible conflicts with inside reinforcing steel can be avoided, and also a smaller size hole can be left for subsequent repair. Finally, small cores may be the only alternative if standard core specimens are desired; for example, if specimens with length to diameter ratio of two are to be obtained from a thin element.

Finite element model

Numerous finite element models are built in the Abaqus environment to investigate the potential effect of core diameter on strength of concrete. The matrix of the finite element model is shown in Table 2. The concrete cylinder is built using solid element (C3D8R: eight-node brick element with reduced integration).

Table 2. Different sizes of concrete core.

	Core size [diameter mm (in.) × height mm (in.)]				
$h/d = 2$	152×305 (6×12)	127×254 (5×10)	101×203 (4×8)	76×152 (3×6)	51×101 (2×4)
$h/d = 1.75$	152×267 (6×10.5)	127×222 (5×8.75)	101×178 (4×7)	76×133 (3×5.25)	51×89 (2×3.5)
$h/d = 1.5$	152×229 (6×9)	127×191 (5×7.5)	101×152 (4×6)	76×114 (3×4.5)	51×76 (2×3)
$h/d = 1.25$	152×191 (6×7.5)	127×159 (5×6.25)	101×127 (4×5)	76×95 (3×3.75)	51×64 (2×2.5)
$h/d = 1$	152×152 (6×6)	127×127 (5×5)	101×101 (4×4)	76×76 (3×3)	51×51 (2×2)

Damage plasticity model is considered in the concrete model in Abaqus. As shown in Fig. 10, the unloaded response of the concrete specimen seems to be weakened because the elastic stiffness of the concrete appears to be damaged or degraded. Figure 10 shows the degradation of the elastic stiffness on the strain softening branch of the stress-strain curve is characterised by two damage variables, d_t and d_c , which can take values from zero to one. Zero represents the undamaged material where 1 represents a total loss of strength (Abaqus User Manual, 2016). E_0 is the initial (undamaged) elastic stiffness of the material, and $\tilde{\varepsilon}_c^{pl}$, $\tilde{\varepsilon}_t^{pl}$, $\tilde{\varepsilon}_c^{in}$, $\tilde{\varepsilon}_t^{in}$ are the strains – compressive, tensile, compressive inelastic, and tensile inelastic, respectively.

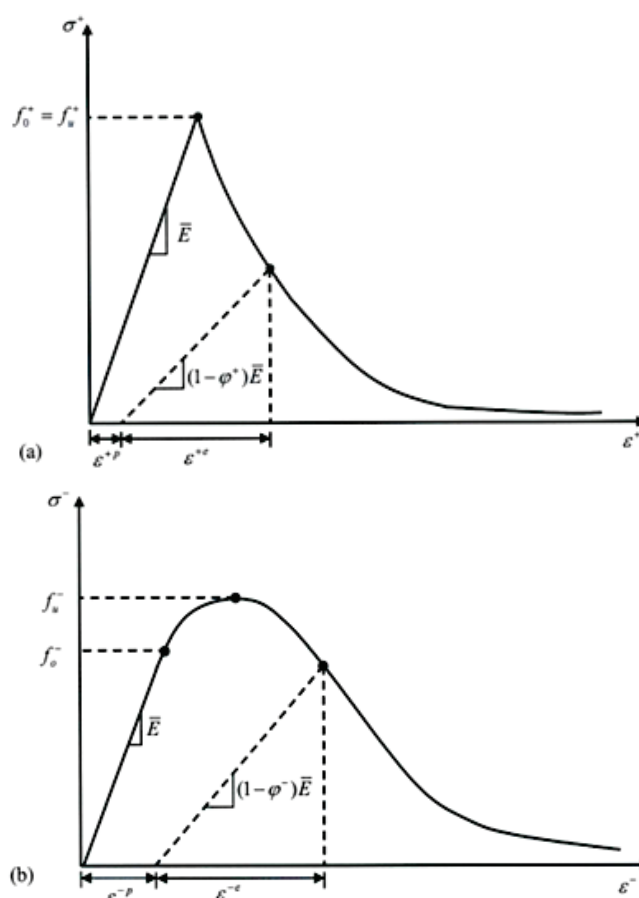


Figure 9. Concrete behaviour under uniaxial loading in: a) tension; b) compression (ABAQUS, 2016).

The stress-strain relations under uniaxial tension and compression are considered in Eqs.(2) and (3):

$$\sigma_t = (1 - d_t) E_0 (\varepsilon_t - \tilde{\varepsilon}_t^{pl}), \quad (2)$$

$$\sigma_c = (1 - d_c) E_0 (\varepsilon_c - \tilde{\varepsilon}_c^{pl}). \quad (3)$$

The input of concrete plastic damage properties for Abaqus model is shown in Table 3, /21/. For concrete, the following properties are considered: elastic modulus of 3450 MPa, Poisson's ratio 0.2, density $6.22 \times 10^{-8} \text{ kg/mm}^3$.

Table 3. Damage properties of concrete, /21/.

Plastic Properties of Concrete					
Dilation Angle (ψ)	Eccentricity	f_{bo}/f_{co}	K	Viscosity Parameter	
38°	0.1	1.12	0.667	0	
Concrete Compression			Tension Behavior		
Tension Recovery		1.0	Tension Recovery		0
Yield Stress (MPa)	Inelastic Strain	Damage Parameter	Yield Stress (MPa)	Inelastic Strain	Damage Parameter
15.0	0	0	1.99893	0	0
20.197804	0.0000747307	0	2.842	0.00003333	0
30.000609	0.0000988479	0	1.86981	0.00016	0.406
40.303781	0.000154123	0	0.862723	0.00028	0.696
50.007692	0.000761538	0	0.226254	0.000685	0.92
40.236090	0.002557559	0.195402	0.056576	0.001087	0.98
20.236090	0.005675431	0.596382			
5.257557	0.011733119	0.894865			

A fixed boundary condition is assigned to the bottom surface of the concrete cylinder. A linear deformation controlled load is applied from the top surface of the cylinder, as shown in Fig. 11.

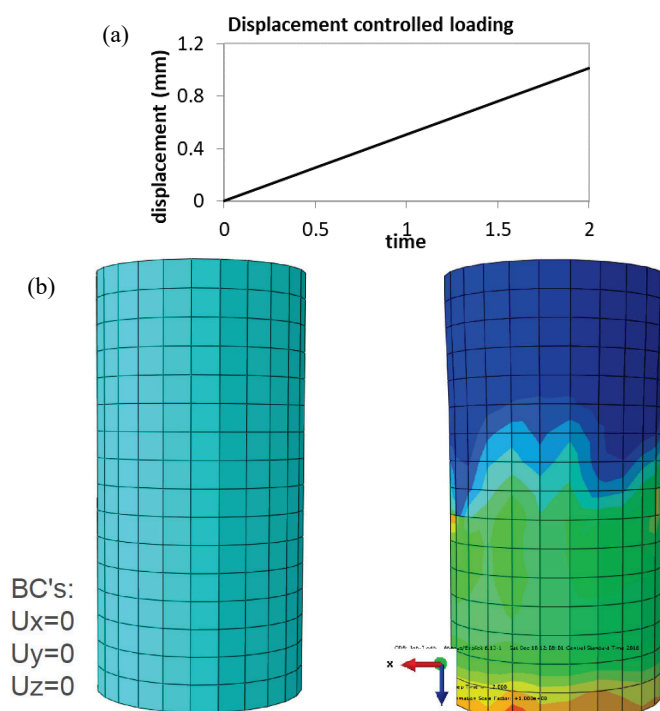


Figure 10. Finite element analysis: (a) displacement controlled loading; (b) FE model for 50 mm $\times$ 100 mm core in Abaqus.

Mesh convergence study

To determine whether the mesh size used for these analyses is satisfactory, a mesh convergence study is performed. The results obtained, as shown in Fig. 12, are compared with each of them. The difference in results (concrete strength) obtained with the dense and intermediate mesh is less than 1 %. This gives evidence that the finite element approximation has converged, and the results are satisfactory. For this study, 6.35 mm (0.25 in.) is used for all cores during finite element analysis.

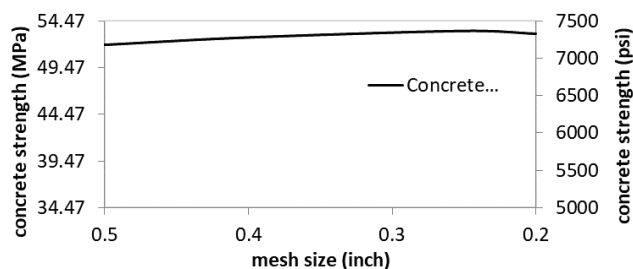


Figure 11. Mesh convergence study for 50 mm $\times$ 100 mm core.

Results from finite element model

Figure 13 shows the effect of different core diameters for ratio of $h/d = 2$. The calculated strengths of all concrete cylinders are similar (less than 2 % variation) even though the diameters are different. The average concrete strength obtained from finite element analysis is 41.5 MPa which is exactly the same with the converted ASTM C 42 (correction factor: 1) and BS 1881 (correction factor: 1) strength. Therefore, for this parametric study, the considered control strength is 41.5 MPa.

Figure 14 shows the effect of different core diameters for ratio of $h/d = 1.75$. The obtained concrete strengths for different diameters are similar (less than 2 % variation). The average concrete strength (41.9 MPa) is determined from all calculated strength values, and the estimated concrete strength is calculated using ASTM (correction factor: 0.98) and BS (correction factor: 0.97) correction factors. The estimated concrete strengths obtained from ASTM (41.0 MPa) and BS (40.6 MPa) are 1.2 % and 2.2 % less than the control strength, respectively.

Figure 15 shows the effect of different (less than 2 % variation in strength) core diameters for ratio of $h/d = 1.50$. The average concrete strength (43.7 MPa) is determined from all calculated strength values, and the estimated concrete strength is calculated using ASTM (correction factor: 0.96) and BS (correction factor: 0.92) correction factors. Estimated concrete strengths obtained from ASTM (41.9 MPa) and BS (40.4 MPa) are respectively 0.95 % more and 2.7 % less than the control strength.

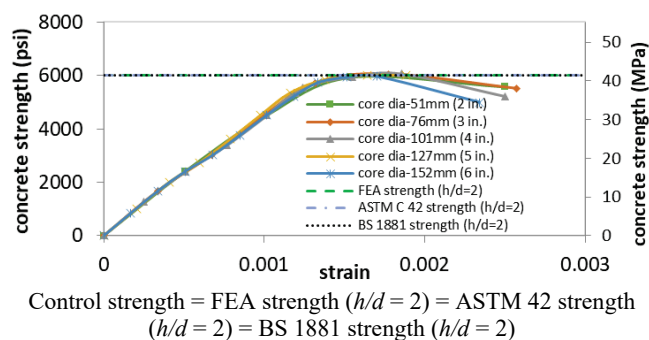
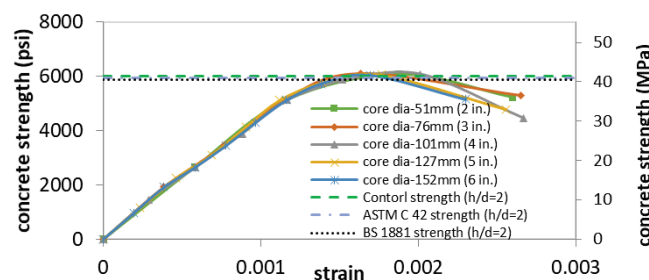
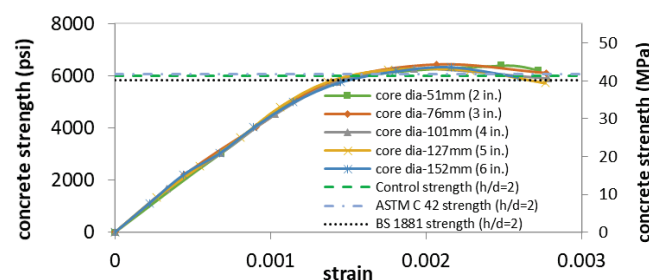
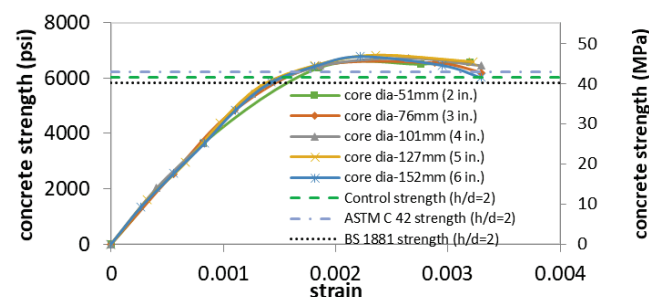
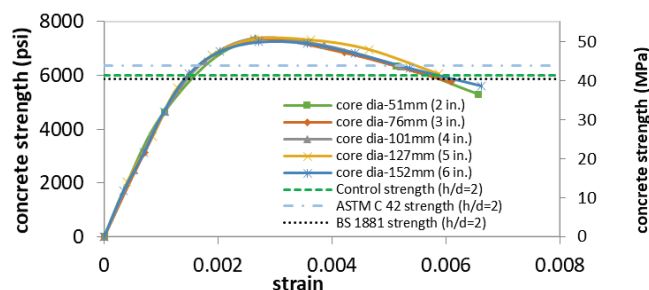
Figure 12. Concrete strength for core with $h/d = 2$.Figure 13. Concrete strength for core with $h/d = 1.75$.Figure 14. Concrete strength for core with $h/d = 1.5$.Figure 15. Concrete strength for core with $h/d = 1.25$.Figure 16. Concrete strength for core with $h/d = 1$.

Figure 16 shows the effect of different core diameters for ratio of $h/d = 1.25$. The achieved concrete core strengths for different diameters are very close to each other (less than 2 % variation). The average concrete strength (46.3 MPa) is

determined from all calculated strength values, and the estimated concrete strength is calculated using ASTM (correction factor: 0.93) and BS (correction factor: 0.87) correction factors. The estimated concrete strengths obtained from ASTM (43.0 MPa) and BS (40.3 MPa) are respectively 3.5 % more and 2.9 % less than the control strength.

Figure 17 shows the effect of different core diameters for ratio of $h/d = 1.00$. The calculated concrete strengths are identical (less than 2 % variation) for different core diameters. The average concrete strength (50.5 MPa) is determined from all calculated strength values, and the estimated concrete strength is calculated using ASTM (correction factor: 0.87) and BS (correction factor: 0.80) correction factors. The estimated concrete strengths obtained from ASTM (43.9 MPa) and BS (40.4 MPa) are respectively 5.5 % more and 2.7 % less than the control strength.

CONCLUSIONS

Considering all field monitored data and finite element analysis, the following conclusions can be drawn:

- According to the field obtained results, no specific trend is found for different diameters and height-to-diameter ratios, whereas ASTM C 42 states the concrete core strength increases with the decreasing value of h/d ($h/d = 2$ to $h/d = 1$). In order to understand the overall strength of concrete, it is always better to extract more samples from a structural member of the building. It is only possible only when engineers extract smaller diameter concrete cores.
- Based on finite element analysis, it can be stated that the core diameter does not have any significant effect on the concrete strength. The concrete strength largely depends on core height-diameter ratio, and strength correction factors for core height-to-diameter ratio as expressed in ACI 214.4R-10 is enough to demonstrate the concrete strength for any core diameter. In that case, multiple core samples with smaller diameter (51 mm) can be taken from any particular critical structural member (column or beam).
- It is also recommended to conduct rigorous experimental study and numerous amounts of pilot projects to establish using 51 mm (2 in.) diameter cores in inspecting existing buildings to estimate concrete strength.
- Core micro-cracking may affect a lot in estimating the concrete strength. This issue needs to be studied in the future study with greater importance.

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