Characteristic concrete compressive strength of existing structures—Evaluation of EN 13791:2019 for small sample sizes

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Abstract

In the sense of resource-efficient handling of existing structures, conversion should be given priority over demolition and reconstruction of buildings. Accordingly, the assessment of existing structures is becoming increasingly important. Until now, the characteristic concrete compressive strength as one of the most important factors for the evaluation of existing structures has been determined at European level according to EN 13791:2007. Today, the new EN 13791:2019 replaces EN 13791:2007. Especially for small sample sizes of drill cores ($3 \leq n \leq 7$), the introduction of EN 13791:2019 results in significant changes for the determination of the characteristic in situ concrete compressive strength. In addition, there is only limited background information available for the statistical robustness of the new methods. Therefore, the methods for the determination of the characteristic concrete compressive strength of existing structures according to EN 13791:2019 have been evaluated with the help of an existing drill core database established at the TU Kaiserslautern.

KEYWORDS
assessment value, concrete compressive strength, existing structures, in situ

1 | INTRODUCTION

A sustainable approach to existing structures is essential with regard to life-cycle assessments and their cultural value. Wherever possible, conversion should be given priority over demolition and reconstruction of buildings.

In the case of conversion work on existing structures, an intervention in load-bearing structures often is unavoidable. Due to a change of use, this is often combined with an adjustment of load levels. Depending on the changes during conversion measures and adjustments of load levels, individual components may be verified according to the original structural engineering regulations or have to be assessed according to the currently valid standards. For the assessment of existing reinforced concrete structures, the concrete compressive strength is usually a significant parameter. At the same time,
structural engineering documents or results of quality tests of concrete from the construction period often are not available for many existing structures. Therefore, among other things, a well-founded investigation of existing structures is necessary to evaluate refurbishment options on the basis of the concrete compressive strength.

At the European level, the characteristic concrete compressive strength has been determined on the basis of the methods of EN 13791:2007.2 Due to possible over-estimation, in Germany, new approaches were introduced with DIN EN 13791/A20:2017.3 Now, the new EN 13791:20194 has been published. At the same time, only limited background information is available on the statistical robustness of the new methods. To bridge this gap, EN 13791:20194 has been evaluated within the framework of the research project DBV 3175 at TU Kaiserslautern. This paper gives an overview about these results.

The aim of the investigation was to be able to make a statement about the statistical robustness of the methods, backed up by tests. These results should be used as a basis for well-founded recommendations in order to be able to reliably determine the characteristic in situ concrete compressive strength in the future.

2 | DETERMINATION OF CHARACTERISTIC CONCRETE COMPRESSION STRENGTH OF EXISTING STRUCTURES ACCORDING TO EN 13791 FOR SMALL SAMPLE SIZES

2.1 | EN 13791:2007/DIN EN 13971:2008

Until now, the assessment of the compressive strength of concrete in structures or parts of structures was normatively regulated in Germany in DIN EN 13971:20086 with National Annex DIN EN 13791/A20:2017.3 In EN 13791:20072 and thus also in DIN EN 13971:2008,6 a distinction has been made between two evaluation methods, Approach A (n > 15) and Approach B (3 ≤ n ≤ 14), due to the sample size n (see Figure 1) of drill cores.

2.2 | DIN EN 13971/A20:2017

The National Annex DIN EN 13791/A20:20173 was introduced by Germany in 2017, as the evaluation methods of EN 13791:20072 for small sample sizes usually produced a significant overestimation of the characteristic in situ concrete compressive strength (see References 7–13).

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**FIGURE 1** Determination of the characteristic in situ concrete compressive strengths according to EN 13791:20072

| n  | 3–6 | 7–9 | 10–14 |
|----|-----|-----|-------|
| k  | 5   | 6   | 7     |

\[
f_{ck, is} = \min \left\{ \frac{f_{m(n),is} - k}{f_{is,\text{lowest}} + 4} \right\}
\]

use:

\[
f_{ck, is} = \min \left\{ \frac{f_{m(n),is} - k_2 \cdot s_x}{f_{is,\text{lowest}} + 4} \right\}
\]

use:

\[k_2 = 1.48\text{ (in Germany; may be specified in the National Annex)}\]
According to DIN EN 13791/A20:2017,\(^3\) the characteristic compressive strength for existing structures is determined according to the Modified Approach A or the Modified Approach B depending on the number of drill cores \(n\) and the coefficient of variation \(v\) (see Figure 2).

The Modified Approach A shall be used for the determination of the characteristic in situ concrete compressive strength if a sample size \(n \geq 9\) is available or if a coefficient of variation \(v > 0.20\) results for a sample size \(3 \leq n \leq 8\). The determination of the characteristic in situ concrete compressive strength for a sample size \(3 \leq n \leq 8\) and \(v \leq 0.20\) may be carried out according to the Modified Approach B. As shown in Figure 2, the factor \(k_3\) is based on the determination of the characteristic in situ concrete compressive strength according to EN 1990:2002\(^{14}\) using a normal distribution and a minimum coefficient of variation \(v_{x,\text{min}} = 0.09\).

### Figure 2

Determination of the characteristic in situ concrete compressive strengths according to DIN EN 13791/A20:2017\(^3\) and background of \(k_3\)^{7,8}

| \(n\) | \(k_n\) | \(v_{x,\text{min}}\) | \(1 - k_n \cdot v\) | \(k_3\) | \(v\) |
|------|--------|----------------|-----------------|-------|-----|
| 3    | 3.37   | 0.09           | 0.70            | 0.70  | 0.70|
| 4    | 2.63   | 0.09           | 0.76            | 0.75  |     |
| 5    | 2.33   | 0.09           | 0.79            | 0.75  |     |
| 6    | 2.18   | 0.09           | 0.80            | 0.80  |     |
| 7    | 2.08   | 0.09           | 0.81            | 0.80  |     |
| 8    | 2.00   | 0.09           | 0.82            |       |     |

\(f_{c_{k,\text{is}}} = \min \left\{ f_{m(n),\text{is}}, \frac{k_3}{f_{a,\text{lowest}} + 4} \right\}\)

\(k_3 = 0.70\) for \(n = 3\), \(0.75\) for \(4 \leq n \leq 5\), and \(0.80\) for \(6 \leq n \leq 8\).

\(k_n\) according to EN 1990:2002

2.3 | **EN 13971:2019**

EN 13971:2019\(^4\) formally replaces the previous version of the standard EN 13791:2007.\(^2\) In many cases, EN 13971:2019\(^4\) refers to national rules or allows the introduction of such rules. Especially for small sample sizes \((3 \leq n \leq 7)\), the introduction of EN 13971:2019\(^4\) results in significant changes in the determination of the characteristic in situ concrete compressive strength. A few modifications have also been implemented for large sample sizes. For the purpose of completeness, Figure 3 shows the evaluation method for larger sample sizes, too.

While updating EN 13971, the sample size was adjusted (EN 13791:2007: \(n \geq 15\); EN 13791:2019: \(n \geq 8\)), \(k_n\) was determined as a function of the sample size according to EN 1990:2002\(^{14}\) and a minimum coefficient of variation \(v_{x,\text{min}} = 0.08\) was defined. The given method hereby approximately corresponds to the method according to DIN EN 13791/A20 from Germany for large sample sizes. However, DIN EN 13791/A20 does not take into account the "minimum value criterion" \((f_{c,\text{is},\text{lowest}} + M)\). It should be noted that the equation of the Modified Approach A corresponds to that in EN 1990:2002\(^{14}\) and ISO 13822\(^{15}\) for determining the characteristic in situ compressive strength with the assumption of normal distribution. As in Reference 14, the logarithmic normal distribution may also be used in DIN EN 13791/A20\(^7\) and EN 13791:2019\(^4\) instead. EN 13791:2019 also includes an outlier test (Grubbs test) for the first time. In Reference 8, it was shown that the Grubbs test is only effective for large sample sizes.

According to EN 13791:2019,\(^4\) the characteristic in situ concrete compressive strength for small sample sizes can be calculated according to Section 8.1(7) or Section 8.3. In EN13791:2019,\(^4\) new statistical evaluation methods for the determination of the characteristic in situ concrete compressive strength are presented. The procedures are based on both direct and indirect test methods. Figure 4 shows the two new methods available according to EN 13791:2019\(^4\) for small sample sizes of \(3 \leq n \leq 7\), with the possibility of national modifications.
FIGURE 3  Determination of the characteristic in situ concrete compressive strengths according to different generations of EN 13791 for large sample sizes

EN 13791:2007
\[ n \geq 15 \]

Approach A
\[ f_{ck,ls} = \min \left( \frac{f_{m(n),ls} - k_2 \cdot S_x}{S_{ls,lowest} + 4} \right) \]
use:
\[ k_2 = 1.48 \text{ (Germany)} \]

EN 13791:2019
\[ n \geq 8 \]

\[ \nu > 0.00 \]

Section 8.1(1) to 8.1(6)
\[ f_{ck,ls} = \min \left( \frac{f_{m(n),ls} - k_1 \cdot S_x}{S_{ls,lowest} + M} \right) \]
mit:
\[ S_{x,min} = 0.08 \cdot f_{m(n),ls} \]
\[ k_1 \text{ according to DIN EN 1990:2002 for} 3 \leq n \leq 7 \]

DIN EN 13791/A20:2017
\[ 3 \leq n \leq 8 \]
\[ n \geq 9 \]

\[ \nu > 0.20 \]

\[ \nu > 0.00 \]

\[ k_3 \text{ according to DIN EN 1990:2002 for} \]

FIGURE 4  Determination of the characteristic in situ compressive strengths according to EN 13791:2019\(^4\) for a sample size \(3 \leq n \leq 7\)

Drill core tests
\[ 3 \leq n \leq 7 \]

Section 8.1 (7)
\[ V \leq 10 \text{ m}^3 \]

Application criterion: The spread of results is not more than 15% of the mean strength
\[ (R \leq 0.15 \cdot f_{m(n),ls}); R = f_{c,ls,\text{highest}} - f_{c,ls,\text{lowest}} \]

Section 8.3
\[ V \leq 30 \text{ m}^3 \]

Use indirect test methods to find the point with the lowest concrete compressive strength = extraction point for drill cores

\[ f_{ck,ls} = \frac{1}{n} \sum_{i=1}^{n} f_{c,ls,i} \]
According to Section 8.1(7), the characteristic in situ concrete compressive strength for a limited test area ($V \leq 10 \text{ m}^3$ and a maximum of one to three structural elements) can be calculated on the basis of at least three cores. From these three or more cores, the lowest strength $f_{ck,\text{is,lowest}}$ shall be selected, and this corresponds to the characteristic in situ concrete compressive strength $f_{ck,\text{is}}$ according to Section 8.1(7). The condition is that the spread of the test results $R$ is less than or equal to 15% of the mean value $f_{cm(n),\text{is}}$. It can be assumed that this criterion has been taken from the field of conformity control for compressive strength according to EN 206.\(^{16}\)

This condition also applies if the characteristic in situ concrete compressive strength is determined according to Section 8.3. The evaluation according to Section 8.3 is limited to a test area with a concrete volume of $V \leq 30 \text{ m}^3$. First, the location with the lowest concrete compressive strength is to be found by using indirect test methods. At least three cores are then to be taken from this location. The mean value $f_{cm(n),\text{is}}$ from these three or more cores may then be taken as the characteristic in situ concrete compressive strength $f_{ck,\text{is}}$.

The basics of the new methods, as well as their statistical robustness, are not completely recognizable from EN 13791:2019\(^4\) or from the related background document Fpr-CEN/TR 17086:2017.\(^{17}\) In order to be able to evaluate the application of the new methods, the general procedure and the possible results of the characteristic in situ compressive strength were analyzed with the help of an existing drill core database, which was set up at the TU Kaiserslautern within the framework given in References 5,7,8,12,18–20. In most cases, a total sample size of $n_{ges} > 20$ of drill core tests was available.

### 3 | ANALYSIS OF EN 13791:2019, SECTION 8.1(7)

#### 3.1 | General

Within the framework of the DBV 317 research project,\(^5\) a total of 23 existing structures was analyzed. The year of construction varies from 1915 to 1985 and the mean concrete compressive strength from 16 to 66 N/mm\(^2\). On average, $n_{ges} = 22$ drill cores are available per structure. The existing structures range from columns and walls over slabs to bridge abutments. Eleven of these structures complied with the volume limit of $V \leq 10 \text{ m}^3$ and the other 12 structures did not ($V \leq 10 \text{ m}^3$). This allowed the examination of the influence of the volume limit. For each of the existing structure, $n_{ges}$ results from the compressive strength testing of cores are available. According to Section 8.1(7),\(^4\) at least three such results are needed to determine the characteristic in situ compressive strength. The existing structures from the drill core database of TU Kaiserslautern\(^5\) all have a significantly larger number of drill cores. Within the framework of a statistical evaluation, various possible combinations of test results can be formed, each consisting of three compressive strength results from drill cores. These random combinations were automatically generated without possible repetition, so combinations with duplication of the selected drill cores can be excluded. The lowest value $f_{ck,\text{is,lowest}}$ is then selected from these three concrete compressive strength values.

The characteristic in situ compressive strength of each possible combination determined in this way was then compared with the “real” characteristic in situ compressive strength (compare to References 20,21). According to Reference 22, the “real” characteristic in situ concrete compressive strength $f_{ck,\text{is,EC0-ND},n_{ges}}$ results according to EN 1990:2002 Annex D\(^{14}\) using the normal distribution for $v_{x,n_{ges}} \leq 0.20$ and taking into account the total sample size $n_{ges}$. If a coefficient of variation $v_x > 0.20$ is given, the determination of the “real” characteristic in situ concrete compressive strength is also carried out according to EN 1990:2002 Annex D,\(^{14}\) but using the logarithmic normal distribution.\(^{23}\) In case of $v_x \leq 0.20$, the logarithmic normal distribution and the normal distribution provide approximately similar characteristic values. For greater coefficients of variation $v_x > 0.20$, the logarithmic normal distribution is recommended because it cannot deliver negative values.\(^{23}\)

At this point, it should be noted that the evaluation of the new methods can not only be carried out on the basis of a drill core database as described below; furthermore, it can also be carried out using probabilistic and statistic methods, for example, see References 24,25.

#### 3.2 | Possible characteristic in situ concrete compressive strengths and evaluation of the application criterion

The characteristic in situ compressive strengths of each structural component determined during the evaluation according to Section 3.1 are illustrated in Figure 5 as separate scatter plots. In order to enable an evaluation of the application criterion, the formally “invalid” compressive strength results are shown in addition to the “valid” ones. The characteristic in situ compressive strengths are plotted on the y-axis as a function of the number of possible combinations (x-axis), and in total, Figure 5 shows 5456 possible results. In the following Figures 5–8, which are used for analysis according to Section 8.1(7), the characteristic in situ concrete compressive strengths are also shown on the y-axis and the number of possible
combinations on the x-axis. In the case that more than 7750 results are possible, 7750 of these are randomly selected and shown in the respective figure (see Figure 8).

For the example structure in Figure 5, a total sample size of \( n_{ges} = 33 \) results in a total of 5456 possible three-way combinations \( (x_{combined}) \). Of these 5456 possible results, 987 are classified as valid \( (x_{valid}) \) and 4469 \( (x_{invalid}) \) as invalid via the application criterion \( (R \leq 0.15 \times f_{cm(n),is}) \). The coefficient of variation of the drill core compressive strengths related to the total sample size \( n_{ges} \) is given as \( \nu_{x,nges} \). The green line in Figure 4 represents the characteristic in situ compressive strength calculated according to EN 1990:2002 Annex D20 using a normal distribution and taking into account the total

**FIGURE 5** Possible characteristic in situ concrete compressive strengths for Structure 1 according to Section 8.1(7)

**FIGURE 6** Possible characteristic in situ concrete compressive strengths according to Section 8.1(7) and Approach B for Structure 1

**FIGURE 7** Possible characteristic in situ concrete compressive strengths according to Section 8.1(7) and Modified Approach B for Structure 1

**FIGURE 8** Possible characteristic in situ concrete compressive strengths according to Section 8.1(7) for Structure 1 with \( n = 5 \)
sample size \( n_{\text{ges}} \) (\( f_{\text{ck,IS,EC0-ND,ges}} \)). To classify the results from Section 8.1(7)\(^4\) the percentage deviation from the characteristic in situ concrete compressive strength according to EN 1990:2002 Annex D\(^{14}\) (using a normal distribution) \( f_{\text{ck,IS,ECO-ND,ges}} \) is also shown.

Figure 5 illustrates that the application criterion according to Section 8.1(7)\(^4\) does not automatically classify the characteristic in situ concrete compressive strengths with the largest percentage deviation from \( f_{\text{ck,IS,ECO-ND,ges}} \) as invalid but many results with a smaller percentage distance from \( f_{\text{ck,IS,ECO-ND,ges}} \)

It is particularly remarkable that the characteristic in situ concrete strengths with the largest percentage deviations, up to an overestimation of the concrete compressive strength between 50% and 70%, are not excluded by the application criterion. The reason for this is that the individual values on which these characteristic concrete compressive strengths are based only have a small spread \( R \), which is less than 15% of the mean concrete compressive strength. Because no minimum scatter in the form of the spread \( R \), the standard deviation \( s_n \), or the coefficient of variation \( v_n \) was defined, an underestimation of the scatter of the concrete compressive strength can result in an overestimation of the characteristic in situ concrete compressive strength.

If, for example, a minimum coefficient of variation \( v_{x,\text{min}} = 0.09 \) would be applied in addition to the application criterion \( (R \leq 0.15 \times f_{\text{cm(n),IS}}) \), the maximum overestimation of the characteristic in situ concrete compressive strength for the Structure 1 from Figure 4 would be reduced from 67.8% to 21.3%. A minimum coefficient of variation \( v_{x,\text{min}} = 0.09 \) is also the basis of the factor \( k_1 \) in DIN EN 13791/A20:2017.\(^3\) The significant influence of a minimum coefficient of variation \( v_{x,\text{min}} \) is also described in References 7,8,12,22.

### 3.3 Comparison of possible results according to EN 13791:2019, Section 8.1(7), and according to approach B of EN 13791:2007

As already discussed in References 7–13, the determination of the characteristic in situ concrete compressive strength according to Approach B of EN 13791:2007\(^2\) for small sample sizes usually leads to a significant overestimation of the characteristic in situ concrete compressive strength. For this reason, a modification was already made in Germany in 2017 by introducing DIN EN 1791/A20:2017\(^3\) (see Figure 2). The possible characteristic in situ concrete strengths according to DIN EN 13791/A20:2017\(^3\) are discussed in the following Section 3.4.

Figure 6 compares the possible results of an evaluation according to Approach B of EN 13791:2007\(^2\) (see Figure 1) with the possible results according to Section 8.1(7) of EN 13791:2019.\(^4\) In Figure 6, no distinction is made between “valid” and “invalid” results according to Section 8.1(7). With the introduction of the new EN 13791:2019\(^4\) it was expected that the new approaches would reduce the percentage overestimation of the “real” characteristic in situ concrete compressive strength \( f_{\text{ck,IS,ECO-ND,ges}} \) compared to an evaluation according to Approach B of EN 13791:2007,\(^2\) especially for a small sample size.

Figure 6 shows that no significant reduction of the percentage of overestimation can be confirmed on the basis of the results for a sample size of \( n = 3 \). Rather, the percentage of overestimation of the possible results according to both methods is approximately the same in the range of a medium and large total variation coefficient \( v_{x,\text{ges}} \), whereas with a small total coefficient of variation \( v_{x,\text{ges}} \) the percentage of overestimation of \( f_{\text{ck,IS,ECO-ND,ges}} \) can be larger with an evaluation according to Section 8.1(7)\(^4\) than with an evaluation according to Approach B.\(^2\)

### 3.4 Comparison of possible results according to EN 13791:2019, Section 8.1(7), and according to Modified Approach B of DIN EN 13791/A20:2017

Figure 5 shows the comparison of the possible characteristic in situ concrete strengths with \( n = 3 \) according to Section 8.1(7)\(^4\) with the characteristic in situ compressive strength calculated considering \( n_{\text{ges}} \) according to EN 1990:2002 Annex D\(^{14}\) (\( f_{\text{ck,IS,ECO-ND,ges}} \)). The Modified Approach A of DIN EN 13791/A20\(^5\) corresponds to the evaluation according to EN 1990:2002 Annex D\(^{14}\) using a normal distribution.

It should be noted that the possible characteristic in situ concrete strengths according to DIN EN 13791/A20:2017\(^1\) with \( n = 3 \) may also be subject to certain variations. For this reason, Figure 7 compares the possible characteristic in situ compressive strengths of the two approaches (Section 8.1(7) and Modified Approach B with \( v_{x,n=3} \leq 0.20 \)) with \( n = 3 \) for the example structure already considered in Figure 5. The possible overestimations in an evaluation according to the Modified Approach B of DIN EN 13791/A20:2017\(^7\) are generally small and can be considered harmless for a structural evaluation according to References 2,7,13. In Figure 7, no distinction is made between “valid” and “invalid” results according to Section 8.1(7). This differentiation and the percentage of deviation from \( f_{\text{ck,IS,ECO-ND,ges}} \) can be seen in Figure 5.
As already described in the previous Section 3.2, Section 8.1(7) usually results in an overestimation of the characteristic in situ concrete compressive strength \( f_{\text{ck},\text{is,EC0-ND,nges}} \) independent of the existing coefficient of variation.

On the other hand, when evaluating according to the Modified Approach B, depending on the coefficient of variation of the total sample size \( v_{x,\text{nges}} \), both an overestimation and an underestimation of the characteristic in situ compressive strength compared to \( f_{\text{ck},\text{is,EC0-ND,nges}} \) can be identified.

### 3.5 Investigations on the influence of the sample size \( n \) on the possible results according to EN 13791:2019, Section 8.1(7)

According to Section 8.1(7), at least three drill cores are required for the determination of the characteristic in situ compressive strength. The evaluation method according to Section 8.1(7) may be used up to a sample size of \( n = 7 \). For this reason, the influence of the sample size on the possible results of the characteristic in situ compressive strength and its probability of occurrence must also be analyzed. For this purpose, the sample size is increased from \( n = 3 \) to \( n = 4 \) or \( n = 5 \).

Due to the large number of possible combinations of the characteristic in situ compressive strengths (e.g., Structure 1 with \( n = 4 \), \( x_{\text{combined}} = 40,920 \) and with \( n = 5 \), \( x_{\text{combined}} = 237,336 \)), 7750 random results were selected for the illustration in Figure 8. The point cloud of Structure 1 for \( n = 3 \) can already be found in Figure 5. Since an increase in the sample size does not result in a change of the percentage of deviation of the possible characteristic in situ compressive strengths of \( f_{\text{ck},\text{is,EC0-ND,nges}} \), this deviation is not shown in the following Figure 8. By increasing the sample size (to \( n = 4 \) or \( n = 5 \)), the characteristic in situ compressive strengths with the largest percentage deviation from \( f_{\text{ck},\text{is,EC0-ND,nges}} \) (sample size \( n = 3 \), see Figure 5) are eliminated, as these can no longer become decisive according to Figure 4. It is noticeable that by increasing the sample size \( n \), the percentage of valid results is reduced.

An overview of the development of the valid results of the characteristic in situ compressive strength for the components with a concrete volume of \( V \leq 10 \text{ m}^3 \) is shown in Figure 9 (left). Independent of the mean concrete compressive strength, the coefficient of variation, or other values, the percentage number of valid results ("valid" according to the application criterion) is reduced by increasing the number of drill cores.

Figure 9 (center) shows the development of the mean spread \( R_m \), which can be calculated as the mean value from the spreads of the possible combinations \( x_{\text{combined}} \). The percentage change of the mean spread \( R_m \) is decisive, as it allows a comparison between the existing structures (Figure 9 right). This percentage change in the mean spread \( R_m \) is between 30% and 40% for all 11 structures or components (with \( V \leq 10 \text{ m}^3 \)) when the sample size is increased from \( n = 3 \) to \( n = 5 \).

While the mean spread \( R_m \) is subject to change due to an increase in the sample size \( n \), the mean value of the mean concrete compressive strength \( f_{\text{cm}(n),\text{is}} \) (for \( n = 3 \), \( n = 4 \), and \( n = 5 \)) remains constant according to the law of large numbers. The mean concrete compressive strength \( f_{\text{cm}(n),\text{is}} \) was determined from the mean values of the individual combinations with \( n = 3 \), \( n = 4 \), and \( n = 5 \) and corresponds to the mean concrete compressive strength that can be calculated using the total sample size \( n_{\text{ges}} \).

**Figure 9** Development of the permissible results (left), development (center), and percentage change (right) of the mean spread \( R_m \) as a function of the number of drill cores \( n \) with \( V \leq 10 \text{ m}^3 \).
The reduction of the valid results (see Figure 9 left) can be explained by the mean spread $R_m$ increasing with the sample size and the constant mean concrete compressive strength $f_{cm(n),is}$. To be able to evaluate the application criterion, not only the “valid” but also the formally “invalid” compressive strength results are shown.

4 | ANALYSIS OF EN 13791:2019, SECTION 8.3

4.1 | General

In addition to Section 8.1(7), Section 8.3 of EN 13791:2019 also offers the possibility to calculate the characteristic in situ compressive strength for a limited volume of $V \leq 30 \text{ m}^3$ based on at least three compressive strength tests of drill cores. Within the framework of the research project DBV 317, the method according to Section 8.3 was investigated with the help of eight components. Compared to Section 8.1(7), the number of components is significantly lower than 23, as the drill core database contains only a few structures where a sufficient number of rebound hammer tests (RBH tests) have been carried out. However, there is a relatively wide range of mean in situ compressive strengths ($f_{cm(n),is}$ 22.5 N/mm² to 54 N/mm²) and associated rebound numbers (RB numbers) in the test areas.

The characteristic in situ compressive strength of each possible combination determined according to Section 8.3 was then compared with the “real” characteristic in situ compressive strength as in the analysis of Section 8.1(7). By comparing the characteristic in situ concrete compressive strength determined according to this section with the “real” characteristic in situ concrete compressive strength ($f_{ck,is,EC0-ND,nages}$: $v_{nages} \leq 0.20$; $f_{ck,is,EC0-LND,nages}$: $v_{nages} > 0.20$ see Reference 21), the new assessment method can be evaluated.

Extensive practical structural analyses carried out by the TU Kaiserslautern serve as the basis for these investigations. In most cases, a total sample size of $n_{ges} > 20$ of drill core tests was available.

4.2 | Allocation of drill cores to RBH points

In the first step, the respective drill cores from the structural investigations have to be assigned to the RBH points. This assignment forms the basis for the following determination of the characteristic in situ compressive strength. According to Section 8.3, the drill cores have to be taken from the area around the point with the lowest result from the indirect test. However, a more detailed definition of this area is not given. In order to be able to carry out an evaluation according to Section 8.3 (uniformly for all structures), a catchment area of the RBH points is defined in the DBV 317 research project. For this purpose, the pivot radius of the core drilling machine was used, which is a maximum of 70 cm from the center of the RBH points. Figure 10 shows an example of this assignment for Structure 4 (test areas D, E, and F) from Reference 5. By grinding the surface before the RBH tests, a carbonation depth of <5 mm was ensured, and thus, the requirements according to DIN EN 12504–2:2012 were followed.

All drill cores lying within this radius, as well as those that are tangent to the circular line, are assigned to the corresponding RBH point in the respective evaluation. Based on this assignment of the drill cores to the
individual RBH points, it is possible to calculate the characteristic in situ compressive strength according to Section 8.3.4.

4.3 | Possible characteristic in situ concrete compressive strengths and evaluation of the application criterion

The determination of the characteristic in situ compressive strength according to EN 13791:2019,4 Section 8.3 is based on a minimum number of three drill cores per indirect test point. Since each RBH point can often be assigned to more than three drill cores, all three combinations of the core data assigned to an RBH point are formed for the statistical evaluation, analogous to the procedure for the evaluation according to Section 8.1(7). The mean value \( f_{c,m(n)} \) is then calculated from these three drill core compressive strengths. According to Section 8.3 (see Figure 4), this mean value \( f_{c,m(n)} \) corresponds to the characteristic in situ compressive strength \( f_{ck,is} \). The prerequisite for this is that the spread \( R \) of the considered triple combination is not more than 15% of the mean value (see Figure 4).

Figure 11 illustrates the results of the examinations of the evaluation method according to Section 8.34 for the example component ZI Mannheim wall II according to Reference 5. The RB number with the corresponding RBH point on the x-axis is shown in increasing order. To be able to evaluate the application criterion, not only the “valid” but also the formally “invalid” compressive strength results are shown. The characteristic in situ compressive strength according to EN 1990:2002 Annex D14 \( f_{ck,is,ECO-ND,n_{ges}} \), which was calculated taking into account the total sample size \( n_{ges} \), is shown as a reference value (green line).

Similar to the evaluation according to Section 8.1(7), the application of Section 8.3 sometimes significantly overestimates the characteristic in situ concrete compressive strength compared to \( f_{ck,is,ECO-ND,n_{ges}} \), which was calculated based on the total sample size \( n_{ges} \). In addition, Figure 11 shows that the application criterion does not necessarily classify the characteristic in situ concrete compressive strengths with the largest percentage deviation from \( f_{ck,is,ECO-ND,n_{ges}} \) as invalid (regardless of the RBH point) but many results with a smaller percentage distance from \( f_{ck,is,ECO-ND,n_{ges}} \).

In seven of the eight investigated existing structures, the point with the lowest RB number is not also the point with the lowest concrete compressive strength (see Figure 11), although the requirements for the use of the RBH according to DIN EN 12504–2:201226 were respected.

The investigations confirm that only the compressive strength near the surface can be tested by indirect testing methods, and thus, no clear statement about the core strength of the structure is possible (see Reference 22). The basic assumption underlying Section 8.3, that the point with the lowest concrete compressive strength can reliably be found through RBH tests on existing structures, cannot be confirmed on the basis of the analyzed structural testing.

4.4 | Comparison of possible results according to EN 13791:2019, Section 8.3 and according to Approach B of EN 13791:2007

In line with the procedure for the analysis of Clause 8.1 (7),4 a comparison with the possible results according to
EN 13791:2007 Approach B\(^2\) was also carried out when analyzing the results according to Section 8.3. This comparison is used to determine whether the overestimation of the characteristic in situ concrete compressive strengths for small sample sizes according to Approach B of EN 13791:2007\(^2\) described in References 7–13 is reduced by the new method according to Section 8.3 of EN 13791:2019.\(^4\)

Figure 12 shows the comparison of the possible results in an evaluation according to Approach B\(^2\) with the possible results according to Section 8.3\(^4\) for Structure 4. In Figure 12, no distinction is made between “valid” and “invalid” results according to Section 8.3.

Similar to the evaluation according to Section 8.1(7), the clear overestimation shown by References 7–13 for an evaluation according to Approach B\(^2\) for small sample sizes is not reduced in an evaluation according to Section 8.3\(^4\) (see Figure 12). The differentiation with respect to “valid” and “invalid” results can be found in Figure 11.

In addition, there is the unsuitable use of indirect test methods according to EN 13791:2019, Section 8.3.\(^4\) for locating the point or points with the lowest concrete compressive strength within a test area.

### 4.5 Comparison of possible results according to EN 13791:2019, Section 8.3, and according to Modified Approach B of DIN EN 13791/A20:2017

Figure 11 shows the comparison of the possible characteristic in situ compressive strengths with \(n = 3\) according to Section 8.3 of EN 13791:2019\(^4\) with the characteristic in situ compressive strength \(f_{ck, is, ECO-ND, nges}\) which was calculated taking into account \(n_{ges}\) and according to DIN EN 13791/A20:2017.\(^3\)

It should be noted that the possible characteristic in situ concrete compressive strengths according to DIN EN 13791/A20:2017\(^3\) with \(n = 3\) (Modified Approach B with \(v_{x,n}=3 \leq 0.20\)) may also be subject to certain variations (see Section 3.3). For this reason, Figure 13 compares the possible characteristic in situ concrete compressive strengths of the two methods with \(n = 3\) for Structure 4 already considered in Figure 11. In Figure 13, no distinction is made between “valid” and “invalid” results according to Section 8.1(7), and the distinction can be seen in Figure 11.

The method according to Section 8.3\(^4\) leads to an overestimation of the characteristic in situ concrete compressive strength compared to \(f_{ck, is, ECO-ND, nges}\) irrespective of the
coefficient of variation present and the RBH point investigated.

On the other hand, when evaluating according to the Modified Approach B, depending on the coefficient of variation of the total sample size $v_{x,nges} \leq 0.09$ in Figure 13, there is an underestimation of the characteristic in situ concrete compressive strength compared to $f_{ck,is,EC0-ND,nges}$ can be identified.

For low coefficients of variation $v_{x,nges}$, as in the case of Structure 4 with $v_{x,nges} = 0.09$ in Figure 13, there is an underestimation of the characteristic in situ concrete compressive strength according to the Modified Approach B compared to $f_{ck,is,EC0-ND,nges}$.

4.6 Investigations on the influence of the sample size $n$ on the possible results according to EN 13791:2019, Section 8.3

According to EN 13791:2019 Section 8.3, at least three drill cores ($3 \leq n \leq 7$) are required for the determination of the characteristic in situ compressive strength. For this reason, the influence of the sample size on the possible results of the characteristic in situ compressive strength has to be investigated, too. By increasing the sample size from $n = 3$ to $n = 4$ and $n = 5$, the percentage of valid results was reduced using the application criterion as in an evaluation according to DIN EN 13791:2019, Section 8.1(7).

Figure 14 shows the possible characteristic in situ concrete compressive strengths for Structure 4 according to Section 8.3 for a sample size of $n = 5$. At the RBH point E4 in Figure 14, no characteristic in situ concrete compressive strength can be determined for $n = 5$, as only four drill cores (see Figure 10) could be allocated to this RBH point.

An improvement of the correlation between RB number and concrete compressive strength as well as a reduction of the overestimation of the “real” characteristic in situ concrete compressive strength $f_{ck,is,EC0-ND,nges}$ cannot be observed by increasing the sample size (see Figure 14).

5 COMPARISON OF THE POSSIBLE RESULTS OF AN EVALUATION ACCORDING TO EN 13791:2019, SECTION 8.1(7), AND ACCORDING TO SECTION 8.3

According to EN 13791:2019, two evaluation methods for small sample sizes ($3 \leq n \leq 7$) are available for determining the characteristic in situ concrete compressive strength. In the following, the two evaluation methods are directly compared with each other. The possible characteristic in situ concrete compressive strengths resulting from the evaluation of the two methods with a sample size of $n = 3$ as well as $f_{ck,is,EC0-ND,nges}$ (green line) are compared for Structure 4 in Figure 15.

The direct comparison of the possible characteristic in situ concrete compressive strengths according to EN 13791:2019, Section 8.1(7) and Section 8.3, in Figure 15 shows that the overestimation of the “real” characteristic in situ concrete compressive strength $f_{ck,is,EC0-ND,nges}$ of both methods is quite similar.

6 CONCLUSION

The new edition of EN 13791:2007 was expected to reduce the percentage of overestimation for the “real” characteristic in situ concrete compressive strength $f_{ck,is,EC0-ND,nges}$ which results from Approach B of EN 13791:2007, especially for small sample sizes. The investigations carried out in the context of a research project on the basis of a drill core database show that these expectations cannot be validated for the new evaluation methods according to EN 13791:2019, Section 8.1(7) and Section 8.3.

The percentage of overestimation of the concrete compressive strength in an evaluation according to the old method of Approach B and that in an evaluation according to the new method according to Section 8.1(7) and Section 8.3 is almost the same for the existing structures considered in Reference 5.

Due to the partly significant overestimation of the “real” characteristic in situ concrete compressive strength $f_{ck,is,EC0-ND,nges}$ by EN 13791:2019, Section 8.1(7) and Section 8.3, either an adaptation of the method or the use of the Modified Approach B of DIN EN 13791/A20:2017 for small sample sizes ($3 \leq n \leq 7$) is recommended.

The modification of the procedures from EN 13791:2019 could be done, for example, by introducing a minimum coefficient of variation (see Section 3.2) and defining the application criterion via a more robust estimator.

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DATA AVAILABILITY STATEMENT
Data are openly available in a public repository that does not issue DOIs. The data that support the findings of this study are openly available in References 7,8,19.

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