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DETERMINATION OF IN-SITU CONCRETE COMPRESSIVE STRENGTH UNDER CONSIDERATION OF REARRANGEMENT EFFECTS

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Abstract.

For the design of existing structures the concrete compressive strength and the derived mechanical parameters are of central importance. Due to safety reasons the compressive strength of existing concrete is usually set comparatively low and thus underestimated. The reasons for this are the limited numbers and the large scatter of material properties of the drill cores, which are the basis for the experimental determination of the compressive strength. In contrast to experimental tests the load in structural components of buildings usually is transferred over the area with higher stiffness and consequently with higher compressive strength. Therefore, existing strength variations within a component only play a subordinate role due to rearrangement effects. This paper deals with the experimental and numerical analysis of such rearrangement effects in order to determine the concrete compressive strength of existing structures more realistic and lay a basis for a economical design. By considering these rearrangement effects more realistic during the design of existing concrete structures, a higher number of existing buildings can be maintained without structural measures. The preservation of existing structures is not only decisive from an economic, sustainable and resource-saving point of view, but also represents an added value for cultural and social aspects.

Keywords: Existing structures, in-situ concrete compressive strength, recalculation.

1. Introduction

The preservation of existing structures is of great interest, because of its contribution to sustainability and resource conservation as well as economic reasons. In the case of existing buildings, maintenance, reconstruction and revitalisation works often take place due to adjustments or changes of use. In terms of structural design the stability of the structure has to be verified in accordance with the currently valid regulations. The determination of the characteristic concrete compressive strength of existing structures, which forms the basis for the design according to the valid regulations, can currently be defined on European level according to EN 13791. The standard EN 13791:2007 [1] introduced in 2007 was replaced in 2018 by a new draft prEN 13791:2018 [2].

To access the concrete compressive strength of structures or parts of structures, EN 13791:2007 [1] contains the two approaches A ($n \geq 15$) and B ($3 \leq n \leq 15$) depending on the number of the drill cores samples n. Due to the weaknesses of Approach B of EN 13791:2007 [1], which (according to [3] and [4]) can significantly overestimate or underestimate the characteristic in-situ concrete compressive strength as a function of the coefficient of variation of the basic population, adjustments were made in this respect both in the Annex A20 (DINăENă13791/A20:2017 [5]) introduced in Germany in 2017 and in the development of prENă13791:2018. The regulations introduced with DINăEN 13791/A20:2017 [5] and the associated background are presented in detail in [3] and [4].

Analogous to EN 13791:2007 [1], the evaluation of the characteristic compressive strength of structural concrete according to prENă13791:2018 [2] can also be carried out by means of drill core tests. Instead of the approaches A ($n \geq 15$) and B ($3 \leq n \leq 14$) of EN 13791:2007, prEN 13791:2018 [2] only provides an evaluation method that must be based on at least eight drill cores.

For a limited test range, prEN 13791:2018 [2] provides two options to determine the characteristic in-situ concrete compressive strength based on at least three drill core results. An assessment of the procedures latest introduced in prENă13791:2018 [2] for restricted test areas and small sample sizes is carried out in [6] and is not part of this paper.

2. Scattering of in-situ concrete compressive strength

According to EN 13791:2007 [1], DIN EN 13791/A20:2017 [5] and prEN 13791:2018 [2], the estimation of the scatter of the compressive strength based on the sample number n, regardless whether the scatter is expressed in the form of the

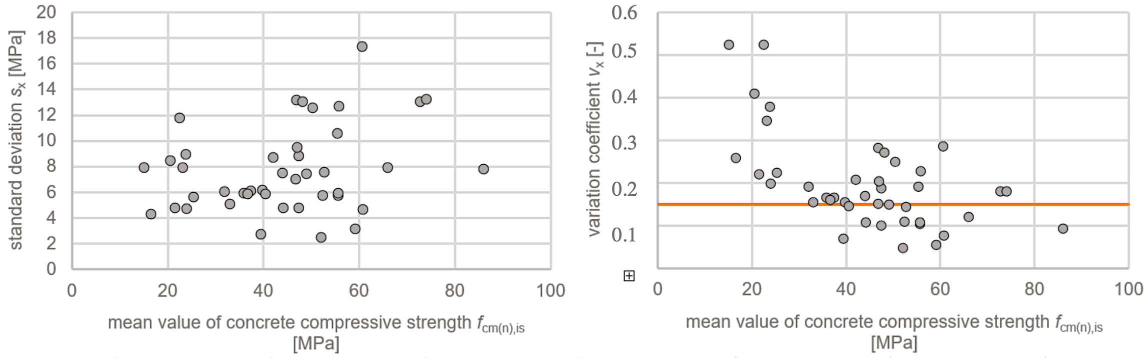

Figure 1. Relationship between standard deviation s_x and mean in-situ concrete compressive strength $f_{cm(n),\,is}(n)$ (left) and relationship between coefficient of variation v_x and mean in-situ concrete compressive strength $f_{cm(n),\,is}$ (right) [4] and [7].

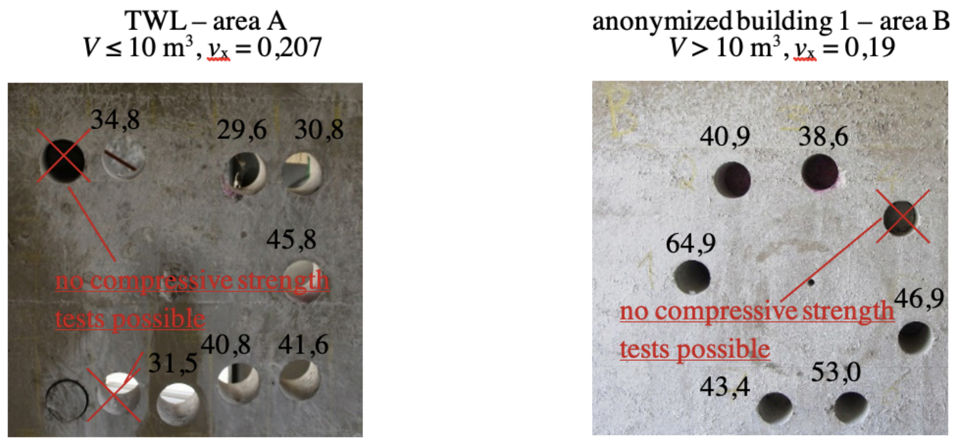

Figure 2. Distribution of drill cores compressive strengths within a test area - left: TWL; right: anonymized building 1 [6].

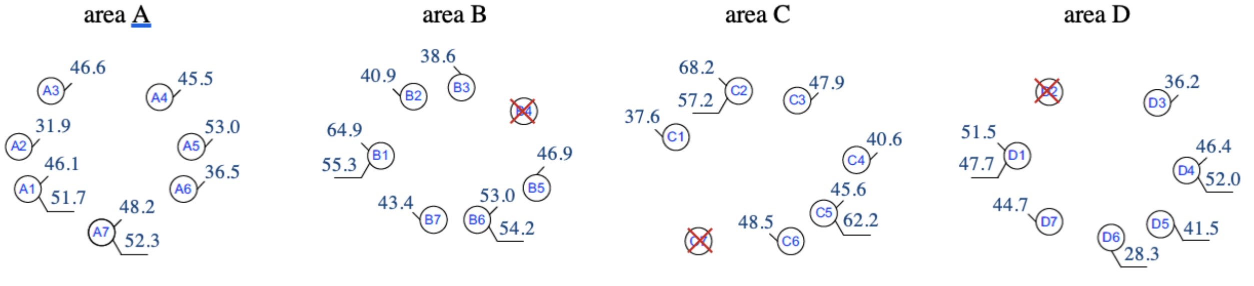

Figure 3. Distribution of the concrete compressive strength within the test areas A to D of the anonymised structure 1.

standard deviation s_x, the coefficient of variation v_x or the spread R, has a decisive influence on the calculated value of the characteristic in-situ compressive strength.

Figure 1 shows the standard deviation s_x (left) and the coefficient of variation v_x (right) in dependency of the mean concrete compressive strength of the existing structure $f_{cm(n),\,is}(n)$ of the test data from [4] and [7]. According to EN 1992-1-1 [8], a coefficient of variation of 0.15 is assumed for the determination of the partial safety factor for concrete γ_c, whereas the coefficients of variation of the existing structures examined in Figure 1 partly exceed this value significantly.

In order to illustrate the significant variation of the compressive strength of the single drill cores within a small area of a given structural element, two drill core removal areas were labelled with the corresponding core compressive strength (in [MPa]) in Figure 2. Two structures with a different volume V (left: $V \leq$ ă10 m^3, right: $V > 10$ m^3, the distinction was made in accordance with EN 13791:2018) but with a similar coefficient of variation v_x were compared. No in-situ compressive strength could be determined at the drill cores (drill core diameter $d = 100$ mm), which were drawn at the points marked with a red cross, e.g. due to insufficient length or existing defects.

Figure 3 shows the test areas A to D of the anonymised structure 1 (test area B is already shown in Figure 2) with the drill core sampling points and the corresponding concrete compressive strength, in order to be able to consider the distribution of the concrete compressive strength not only within one test area, but also over several test areas. At the drill core locations where two concrete compressive strengths are entered in Figure 3, longer drill cores were drawn which could be divided into several drill cores (here: two) to determine the concrete compressive strength.

Due to the manufacturing process, it could be assumed that a horizontal stratification structure is formed and that the concrete compressive strength therefore differs only over the height of the component. On the basis of Figure 3, however, no distribution over the component height or the component width could be derived. Such considerations were also made for other structures investigated within the framework of [4] and [7]. However, no clear distribution of the concrete compressive strength over the height or width of the building component could be derived here either. The variation of the concrete compressive strength within a building component must therefore be considered arbitrary.

The large variation in the scattering of the concrete compressive strength in the form of the standard deviation s_x or the coefficient of variation v_x according to the current evaluation methods from [2] or [6] (annex D) together with the mean concrete compressive strength $f_{cm(n),\,is}$ and the sample number n are the decisive variables for the determination of the characteristic in-situ concrete compressive strength $f_{ck,\,is}$.

When comparing slender with massive structures in terms of design aspects significant differences have to be considered. In slender structures the failure of the weakest part could cause total failure of the structure. In the case of massive structures or components, the load bearing behaviour will cause the redistribution of the stresses resulting from the load within a component towards the areas with a higher strength. Subsequently the influence of areas with lower compressive strength is less than previously assumed via the standard deviation s_x or the coefficient of variation v_x valid also for very slender structures.

Based on this consideration, the handling of the scattering of the concrete compressive strength when calculating the characteristic in-situ concrete compressive strength could changed in order to increase the strength to be used for the assessment. By using outlier tests, which also work for small sample sizes, the scatter can be further reduced by excluding outliers upwards or downwards [9].

In addition, the concrete's long-term effects must be taken into account in the assessment, [10] recommends the coefficient of long-term effects α_{cc} of 0.85 for existing structures. The basis for the evaluation of the coefficient of long-term effects in [10] were long-term load tests on drill cores from various existing structures. Furthermore, the partial safety factor can be reduced according to [11].

First tests concerning the determination of rearrangement effects on structural members with large scattering of concrete compressive strength were carried out by [12]. Here slabs composed of concrete strips of different strength for shear force bearing capacity without shear reinforcement where examined and compared with the shear force bearing capacity of reference slabs homogeneously made of one concrete mixture. Further information regarding these tests can be found in [12]. However, a generally valid statement regarding possible rearrangement effects within components cannot be derived from the six test specimen of [12], especially since a special failure case (shear failure without shear reinforcement) was examined and this information cannot be adapted to other failure cases without further investigations or considerations.

For this reason, the following considerations were made regarding the investigation of rearrangement effects on small scaled tests.

3. Experimental small scale tests to determine effects of rearrangement

The following experimental investigations regarding rearrangement effects in concrete structures and components are carried out on small scale tests in the

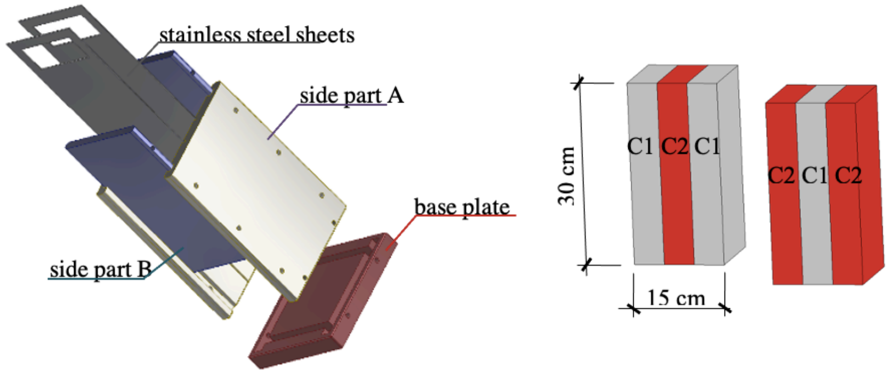

Figure 4. Formwork construction and test specimen construction and dimensions.

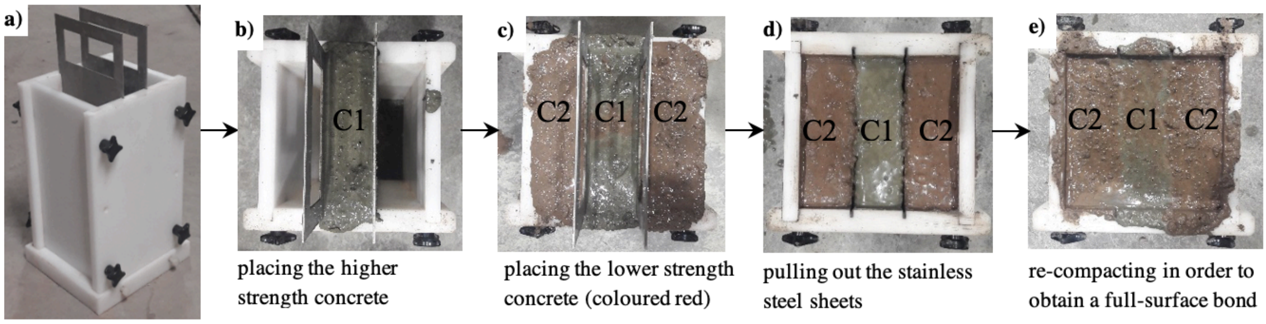

Figure 5. Illustration of the production process of the prism-shaped test specimens with different concrete mixtures.

laboratory of Technical University of Kaiserslautern / Germany (TUK). By producing small scale tests, a test database should be generated that is as extensive as possible in order to enable statistically reliable statements. The aim of these investigations is to proof and qualify the presence and impact of rearrangement effects within a component. Also parameters should be determined which have an influence on the rearrangement effects.

Through numerous structural investigations carried out at the TUK, no clear distribution of the concrete compressive strength as a function of component height or component width within one or more test areas could be determined (cf. Chapter 2).

However, a distribution has to be assumed for the determination of rearrangement effects on small scale tests executed in the laboratory. For this reason, only two limiting cases of vertical layering and horizontal layering of different concrete strength were examined. In existing building structures aădistribution of the concrete compressive strengths will be found, which is irregular and lies in-between these two limiting cases. In this paper the tests results of the vertically layered test specimens are discussed.

3.1. Test program and test setup

The formwork for the prism-shaped test specimens, which are made of different concrete strength and are to be produced fresh in fresh, is shown in Figure 4 and consists of a base plate, four side panels and two stainless steel inserts. To allow frequent use of the formwork and easy stripping, the base plate and the four side parts were made of polyoxymethylene (POM). The side parts are firmly connected to each other with screws, while the side parts A are additionally coupled to the base plate with a screw connection.

The higher strength concrete C1 is always mixed first (C2 in Table 1 and Table 2). Then the concrete is poured halfway either into the middle or the two outer chambers of the formwork and compacted with the a vibrating table. Later the concrete is poured up to the top edge of the formwork and compacted again (Figure 5 b)). The concrete with the lower strength is coloured with red pigments in order to be able to check whether mixing between the concretes has taken place. Here too, the concrete is first poured into the respective chamber of the formwork, compacted to halfway, then filled to the top of the formwork and compacted again (Figure 5ăc)). Afterwards, the stainless steel sheets were removed (Figure 5ăd)). To create a full-surface bond (fresh in fresh) between the concrete layers, the concrete was compacted again (Figure 5ăe)).

In order to check the bond, the test specimens that had been stripped off were reviewed from the outside. In addition randomly selected test specimens were cut into three equally sized pieces with a concrete saw to check whether a full-surface bond between the concrete layers was present even in the part not visible

test series	test specimens geometry		concreting	target strength class		combinations	
	test specimens of different strengths	reference test specimens		C1	C2		
V1	prism	cylinder	B1	C20/25	C12/15	K1 K2	(C1-C2-C1) (C2-C1-C2)
			B2	C30/37	C12/15	K3 K4	(C1-C2-C1) (C2-C1-C2)
			B3	C30/37	C20/25	K5 K6	(C1-C2-C1) (C2-C1-C2)
			B4	C40/55	C30/37	K7 K8	(C1-C2-C1) (C2-C1-C2)
	per concreting 5 × (C1-C2-C1) 5 × (C2-C1-C2)	per concreting 3 × C2 3 × C2	B5	C50/60	C30/37	K9 K10	(C1-C2-C1) (C2-C1-C2)
			B6	C50/60	C40/50	K11 K12	(C1-C2-C1) (C2-C1-C2)
goal V1	Checking whether rearrangement effects can be determined on uniaxial compression strength tests.						

Table 1. Overview of test series 1.

test series	test specimens geometry		concreting	target strength class		combinations	
	test specimens of different strengths	reference test specimens		C1	C2		
V2	prism	cylinder prism	B1	C20/25	C12/15	K1 K2	(C1-C2-C1) (C2-C1-C2)
			B2	C30/37	C12/15	K3 K4	(C1-C2-C1) (C2-C1-C2)
			B3	C30/37	C20/25	K5 K6	(C1-C2-C1) (C2-C1-C2)
			B4	C40/55	C30/37	K7 K8	(C1-C2-C1) (C2-C1-C2)
	per concreting 5 × (C1-C2-C1) 5 × (C2-C1-C2)	per concreting 3 cylinder × C1 3 cylinder × C2 3 prism × C1 3 prism × C2	B5	C50/60	C30/37	K9 K10	(C1-C2-C1) (C2-C1-C2)
			B6	C50/60	C30/37	K11 K12	(C1-C2-C1) (C2-C1-C2)
			B7	C50/60	C40/50	K13 K14	(C1-C2-C1) (C2-C1-C2)
goals V2	Confirmation of the results from V1. Examine influence of the sample geometry (reference sample).						
V2 - HP	prism	cylinder prism	B1-HP B1-HP	C12/15 C20/25		/	C1 = C2
	per concreting 3 ×	per concreting 3 × prism 3 × cylinder	B3-HP B4-HP	C30/37 C50/60			
goals V2 - HP	Checking the influence of the manufacturing process. Checking the influence of the test specimens geometry.						

Table 2. Overview of test series 2.

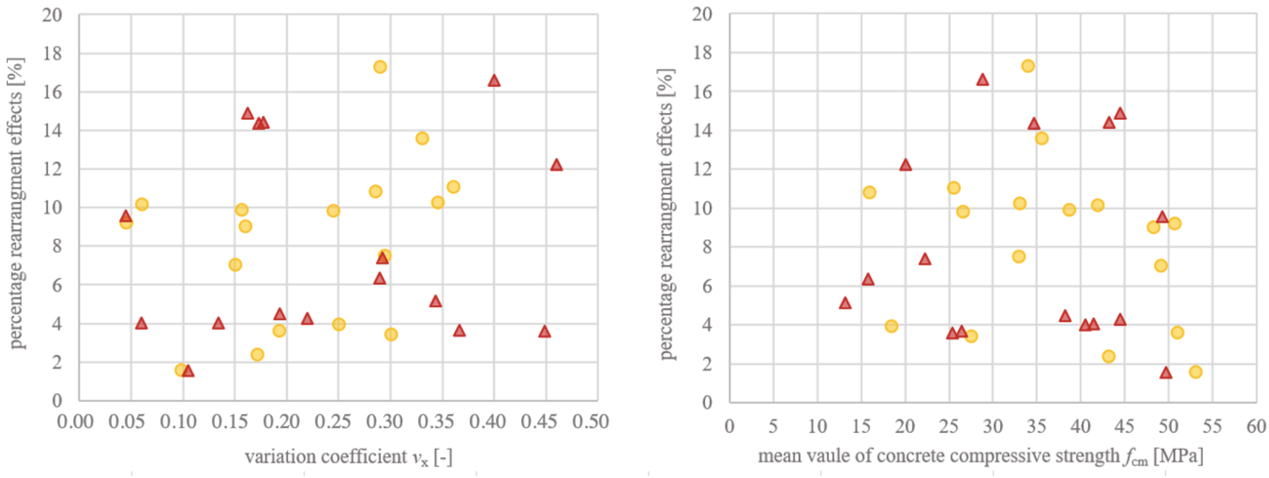

FIGURE 6. Rearrangement effects determined on small part tests in dependency of the coefficient of variation v_x (left) and as a function of the mean value of concrete compressive strength f_{cm} (right), yellow: results of K1, K3, K5, K7, K9, K11, K13, red: results of K2, K4, K6, K8, K10, K12, K14.

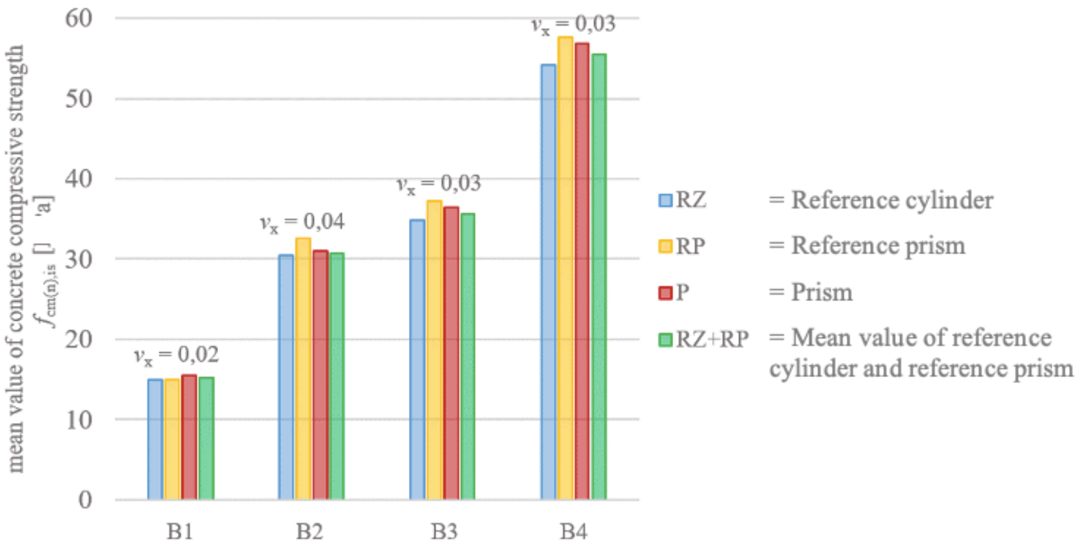

FIGURE 7. Influence of the manufacturing process and the test specimen geometry on the concrete compressive strength.

from the outside. All test specimen fulfilled these criteria.

Table 1 and Table 2 show the test program of test series 1 and test series 2. In test series 1, six concreting operations were carried out to produce prisms from different concretes. Two concretes (C1 and C2) were mixed per concreting and arranged as shown in Figure 4. Three reference cylinder are produced per concrete. The aim of test series 1 was to check whether rearrangement effects can be determined on uniaxial compression strength tests.

In test series 2, prism-shaped test specimens were also produced from different concretes. Prisms as well as cylinders were chosen as reference specimens to check whether the specimen geometry has an influence on the concrete compressive strength. This was also to check whether the choice of cylinders as reference specimens in test series 1 was appropriate. In addition, the production process was to be investigated in test series 2. For this purpose the prism-shaped specimens were also produced as shown in Figure 4, but the same concrete was poured into all three chambers.

4. Results

Figure 6 shows the determined rearrangement effects from test series 1 and 2 in dependency of the coefficient of variation v_x and the average concrete compressive strength f_{cm}. The percentage rearrangement effect was determined by relating the concrete compressive strength of the prism-shaped test specimens made of different concretes to the mean value of concrete compressive strength of the reference specimens $((f_{cm,\,c1} + f_{cm,\,c2} + f_{cm,\,c1})/3)$ or

$((f_{cm,\,c2} + f_{cm,\,c1} + f_{cm,\,c2})\,/3)$. The coefficient of variation, which is present within the prism-shaped test specimens made of different concretes, was also formed using the results of the reference test specimens. For each concrete, at least three concrete compressive strength results were available for the determination of the coefficient of variation. For the prism-shaped test specimens, which are composed of different concretes, the coefficient of variation is determined on the basis of nine or more results (cf. Table 1 and 2). In test series 2, due to the results shown in Figure 7, both the results of the cylinders and those of the prism-shaped test specimens could be used to determine the coefficient of variation.

The results in Figure 6 show that rearrangement effects could also be determined on uniaxial compressive strength tests in which the test specimens exhibit large coefficients of variation (since these consist of different concretes).

The percentage rearrangement effects vary between 2 and 18 %. No clear dependence on the average concrete compressive strength or the coefficient of variation could be established. So far, no other parameter could be identified on which the magnitude of the redistribution effects clearly depends.

On the basis of the test series 2, it could be determined, that the production process has no influence on the experimentally determined concrete compressive strength (see Figure 7). The prisms, which were manufactured from concrete as described in Figure 4 (P), deviate only slightly from the results of the reference cylinders (RZ) or the reference prisms (RP).

Figure 7 shows that the coefficient of variation between the compressive strength results of the different geometries or manufacturing processes is 0.02 to 0.04, which is too low, that an influence of the manufacturing process on the concrete compressive strength can be excluded. Generally, the concrete compressive strength is determined according to the specifications of DIN EN 12390-3 [13].

5. Conclusion and outlook

The theoretical analysis and experimental tests show, that rearrangement effects even occur in comparatively small test specimens consisting of different concretes (with different concrete strengths), which are loaded uniaxially in compression. It could be observed that the prisms (as a function of v_x and f_{cm}) can bear up to 18% more load than the mean value calculated from the reference specimens due to rearrangement effects.

However, it is currently still not quantified on which parameters these effects depend significantly. Therefore in the next step, further small scale tests with horizontal stratification structure will to be carried out to consider the second limiting case for the arrangement of the concrete compressive strength within a component. In order to cover a larger parameter range, additional FEM investigations will be carried out which include the variation of the concrete compressive strength, the coefficient of variation and the dimensions of the specimen. These further investigations are intended to provide a better understanding of the presence and impact of rearrangement effects within structural elements, so that these can ultimately be used in the assessment of existing structures.

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