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Experimental and statistical investigation of the compressive strength anisotropy in structural concrete

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ABSTRACT

This paper offers a new and closer look into the strength anisotropy of concrete by presenting the so far largest experimental programme (290 tests) and by presenting an advanced statistical analysis of the results. The experimental investigation sheds light on the influence of several important design parameters and conditions on the anisotropy. This includes the influence of reinforcement, *w*/*c*-ratio, curing time, load history and structural geometry. For this purpose, cores were drilled out at different angles from beam- and slab specimens for compressive testing. The main findings include: a) the reference cylinder strength (i.e. *w*/*c*-ratio) does not have a significant influence on the anisotropy when the anisotropy is quantified as an absolute difference between the strength of cores drilled in the two directions; b) the anisotropy in structural members without load history is < 5 MPa; c) the anisotropy amounts to 5–10 MPa for members with load history.

1. Introduction

Strength assessment of existing concrete structures is often based on calculation models developed for design of new structures. In this context, the strength parameters adopted in the calculations are usually determined by test of samples taken from the structure. The concrete compressive strength is mostly determined from test of drilled cores, whose compressive strength is subsequently converted to standard cylinder compressive strength. Due to practical reasons, the cores are always drilled perpendicular to the surface of the structure. However, it is known that the core compressive strength is dependent on the drilling direction, [1–5,7]. Hughes and Ash [1], for example, found as much as 50% strength difference between cores drilled parallel and perpendicular to the casting direction. If this directional dependency (i.e. strength anisotropy) is as dramatic as suggested by Hughes and Ash [1], then the current practice - as described above - to estimate the residual capacity of an existing structure may potentially be misleading.

Despite the relevance and the potential impact on current practices for strength assessment of existing structures, the subject of compressive strength anisotropy has received very little attention in the literature, [1–8]. The few previous studies disagree strongly on the magnitude of the anisotropy; absolute as well as relative. Furthermore, it is difficult to draw any general conclusions from the previous studies, mostly due to three shortcomings. These are:

(1) the sample sizes were small,
(2) the conclusions were drawn without a sound statistical analysis of the results,
(3) the geometry and origins of the test specimens were not directly comparable to the cores drilled from actual structural members.

As examples of the mentioned shortcomings, it can be mentioned that Hughes and Ash [1] drew their conclusion based on a comparison of two samples only while Leshchinsky [3] and Ergün & Kürklü [5] drew their conclusions based on a comparison of mean-values without regards to the variances. Johnston [2] and Van Mier [6] studied the anisotropy by testing cubes that were sawn from unreinforced concrete prisms and Leshchinsky [3] drilled cores from unreinforced concrete cubes (200 × 200 × 200 mm).

Hence, even though it is known that the concrete compression strength is direction dependent, it is still debatable how significant the strength anisotropy actually is. Furthermore, the impact of a number of

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The following symbols are used in this paper:: $\text{core}_{\perp}$, Cores drilled perpendicular to the casting direction; $\text{core}_{\parallel}$, Cores drilled parallel to the casting direction; $\text{core}_{\text{hori}}$, Cores drilled horizontally; $\text{core}_{\text{vert}}$, Cores drilled vertically; f_{c}, Concrete compressive strength; $f_{\text{c,core}}$, Concrete core compressive strength; $f_{\text{c,core}\perp}$, Compressive strength of cores drilled perpendicular to the casting direction; $f_{\text{c,core}\parallel}$, Compressive strength of cores drilled parallel to the casting direction; $f_{\text{c,cylin}}$, Reference cylinder compressive strength; $f_{\text{c,core}\theta}$, Influence of design parameters on the anisotropy; $\Delta f_{\text{c,core}}$, Strength anisotropy measured as a strength difference, see Eq. (1); $f_{\text{c,core,hori}}$, Compressive strength of cores drilled horizontally; $f_{\text{c,core,vert}}$, Compressive strength of cores drilled vertically; x, β, θ, Regression coefficients; ε, Random error in the regression models

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important parameters on the anisotropy, e.g. the reference cylinder strength, the presence of reinforcement and the types of structural members, is presently not known or not fully clarified. Finally, the limited literature on this subject does not make clear distinction between strength anisotropy in new structures without load history and in existing structures with load history. Such a distinction is necessary in order to assess whether the anisotropy is mainly a result of the initial casting condition or if it is also affected by e.g. micro damages and cracking from a load history. An answer to the last question is naturally relevant if the compressive strength should be determined for an existing and damaged structure with the aim of estimating the residual load carrying capacity.

This paper offers a fresh and closer look into the strength anisotropy of concrete by presenting a large experimental programme (comprising 290 test results) and by carrying out a thorough and systematic statistical analysis of the experimental results. The primary aim of the investigation is to quantify the strength anisotropy in test specimens of a size that is sufficiently large to resemble real structural members and at the same time avoid the shortcomings identified in the above. Therefore, both beam- and slab specimens are used to investigate the strength anisotropy and how it is affected by a number of design parameters and conditions, which are relevant from a practical point of view. The investigated design parameters and conditions are: a) the reference cylinder strength, b) the presence of reinforcement, c) the curing time, d) the type of structural members (slabs versus beams) and e) the influence of load history. For the statistical analysis of the experimental results, multiple regression models with interactions of explanatory variables are employed. These models enable a detailed analysis of the significance and the magnitude of the anisotropy and the influences of the studied design parameters and conditions.

Following this introduction, Section 2 will describe anisotropy, after which the experimental programme is outlined in Section 3. The statistical approach is set up in Section 4, followed by an outline of results and data analysis in Section 5. Finally, Section 6 provides a summary and discussion, followed by rounding off conclusions in Section 7.

2. Anisotropy

The existence of strength anisotropy in concrete (without a previous load history) is often explained by segregation or water migration in the fresh concrete, which causes weak interfaces or initial micro cracks between the cement paste and the undersurface of the large aggregate particles [1–6,8]. The most commonly used measure for anisotropy is the ratio between the concrete core compressive strength parallel to the casting direction ($f_{c,core\parallel}$) and the core compressive strength perpendicular to the casting direction ($f_{c,core\perp}$), see also Fig. 1. In this paper, the anisotropy will mainly be discussed on the basis of the difference between the core compressive strength parallel and perpendicular to the casting direction, i.e.:

$$\Delta f_{c,core} = f_{c,core\parallel} - f_{c,core\perp} \tag{1}$$

The reason for measuring the anisotropy as an absolute strength difference rather than a strength ratio is that the statistical analyses to be presented below show, that the concrete strength class (i.e. $f_{c,cylin}$) has no significant influence on $\Delta f_{c,\,core}$. Thus, it is simpler to use Eq. (1). A more detailed discussion is provided in Section 6.

3. Experimental programme

The experimental programme to investigate the anisotropy in structural members with and without load history comprises three test series. Each test series consists of a large number of cores drilled from beam- or slab members produced at a local manufacturer of precast concrete elements. In the following, details of each of the test series are provided. Furthermore, Section 3.4 provides details on the performed compression tests.

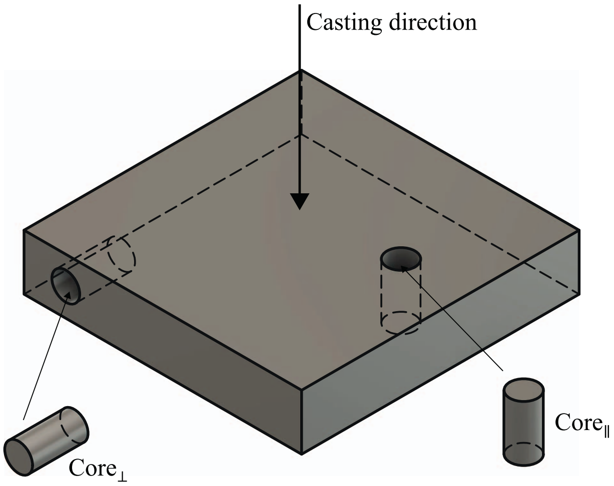

Fig. 1. Illustration of a slab with notation of casting and drilling direction.

3.1. Test series 1

The goal of Test series 1 is to investigate the anisotropy in concrete slabs without load history, i.e. to study anisotropy that cannot be attributed to damages or cracking due to previous loading. The parameters varied in this series are the reference cylinder strength, $f_{c,cylin}$, (i.e. basically the *w*/*c*-ratio) and the presence of reinforcement. The influence of the reinforcement is interesting to investigate because the reinforcement mesh in flat slabs (without shear links) may induce unidirectional micro cracks due to anisotropic shrinkage conditions. These micro cracks may influence the strength anisotropy [8].

The drilled cores in this series were obtained from four slabs with the dimensions 1200 × 1200 × 200 mm. To study the influence of $f_{c,cylin}$, two slabs were cast with a relatively low $f_{c,cylin}$ (Mix A) and two slabs were conducted with a relatively high $f_{c,cylin}$ (Mix B). Details on Mix A and Mix B can be seen in Table 1. To study the influence of the presence of reinforcement for both Mix A and Mix B, one slab contained top and bottom mesh reinforcement and one slab contained no reinforcement. The reinforcement meshes consisted of Ø6 mm rebars per 150 mm in both directions.

Each pair of slabs (Mix A and Mix B) was cast from the same batch of concrete. After casting, the slabs cured for 24 h covered in plastic before they were demoulded, wrapped in plastic and stored indoor until core drilling.

Cores with a diameter of 100 mm were drilled with a water-cooled diamond drill according to the drilling plan displayed in Fig. 2. The drilling plan ensures that all cores were taken from positions not intersected by rebars. 116 drilled cores were used for compressive tests and 110 were used for split tests (the split tests are not are part of this investigation, see [9]). The cores, used for compressive tests, were grinded in both ends to ensure plane loading surfaces. The height of the cores after grinding is shown in Appendix A. The cores were tested after 83 (Mix A) and 91 (Mix B) days, respectively.

Simultaneously with the production of the slabs, Ø100 × 200 mm cylinders were cast from the same concrete batch in order to determine the reference cylinder strength of each concrete mix. The cylinders were cured under the same conditions as the slabs. Table 2 summarises the number of tested cylinders and cores in Test series 1.

3.2. Test series 2

The goal of Test series 2 is to investigate the influence of curing time on the strength anisotropy. For this purpose, cores drilled from beams