

ASSESSMENT OF CONCRETE ANISOTROPY IN RELATION TO THE DIRECTION OF CASTING

Luis E. Kostaschi^{1*}, Ederli Marangon¹, Jorge D. Riera², Francisco J. K. dos Santos³,
Matthews V. V. Bandeira³

ABSTRACT

In numerical predictions of both static and dynamic response of concrete structures, the usual assumption of *global* isotropic behavior is usually accepted, constituting standard practice in structural analysis and design. It has been recognized, however, that *in situ* concrete compressive strength of drilled cores in the direction normal to the direction of casting is somewhat smaller than the strength in the vertical direction. Since the consideration of this factor may reduce model error in numerical schemes that assume isotropic behavior, experimental studies were conducted in order to quantify the degree of anisotropy that may be expected in concrete structures. These initial studies suggest that the effect may result in errors as high as 10% in the estimated carrying capacity, deserving in consequence additional research.

Keywords: Concrete Anisotropy; Compressive strength; Nonhomogeneous quasi-fragile materials; Fracture.

¹ Adjunct Professor, Univ. Federal do Pampa (Unipampa), Av. Tiarajú, 810 - Alegrete - RS - Brazil. CEP: 97546-550 * Corresponding autor: luiskostaschi@unipampa.edu.br

² Invited Professor, Civil Eng. Dept., Univ. Federal do Rio Grande do Sul, Av. Osvaldo Aranha, 99, 3.º floor - - Porto Alegre – RS – Brazil. CEP: 90035-190

³ Master Student, PPEng, Univ. Federal do Pampa (Unipampa), Av. Tiarajú, 810 - Alegrete - RS - Brazil. CEP: 97546-550

1. INTRODUCTION

In reinforced concrete structural analysis and design it is normally assumed that the material is *globally isotropic and homogeneous*. Local departures from this model generally exert a minor influence on observed response and are therefore disregarded. There is overwhelming evidence, however, that in normal concrete *there is some degree of meso-scale orthotropic behavior*, which results from gravitational effects during concrete casting and hardening. This anisotropic behavior may affect structural response predictions in some special situations, as discussed by Riera *et al.* (2017) in connection with applications of the DEM approach.

Evidence concerning the anisotropy of concrete in relation to the direction of casting has been repeatedly observed in the last half century, but remains curiously ignored. Hughes and Ash (1970), for example, report large differences between both the concrete strength, measured both under uniaxial tension and compression, in vertical and horizontal directions.

According to Ozyildirim and Carino (2010), weak interfacial regions tend to occur more frequently under coarse aggregate particles, due to bleeding and other causes. As a direct consequence, in normal concrete, *horizontal initial fractures* - not produced by load applications - may be expected to be more numerous than fractures in other orientations, resulting in a smaller compressive strength in the orientation parallel to the predominant orientation of the cracks, that is, the horizontal plane, in relation to the compressive strength in the vertical direction (Neville, 1996; Suprenant, 1985). This fact has been widely verified in pavement and highway construction: AASHTO T124 (2005) instructions clearly state that the strength of cores drilled in directions parallel to a horizontal plane tends to be lower than the strength of cores drilled in the vertical direction.

The previous considerations lead to two important conclusions: first, horizontal cracks tend to close when subjected to vertical compression and therefore their presence should not influence experimental determinations of the (vertical) unconfined compressive strength. On the other hand, these horizontal cracks may cause a reduction of the influence of confining stresses on the vertical strength, in relation to the effect that might be expected in an isotropic material.

2. PREPARATION OF SAMPLES

The available evidence on the *meso-scale anisotropic behavior of concrete* mentioned above is based mainly on the analysis of concrete cores retired from built structures. The

authors are not aware of laboratory studies designed to examine this effect. Results obtained at Unipampa, RS, Brazil, in a pilot study are described next. Two conventional concrete mixes, identified as materials C30 and C50, were employed in the study. The compositions of both concretes are indicated in Table 1. Brazilian Portland Cement type CP V-ARI was used in all samples. The sand, extracted from the Ibicuí River (RS, Brazil), had particles with high quartz content in the range between 0.15mm and 4.8mm and fineness modulus 1.38, while the coarse aggregate was of basaltic origin with a maximum size of 19mm. Polycarboxilate based superplastifyer with 30% solids content was added to the C50 concrete mix. The water/cement ratio was 0.68 for the C30 concrete and 0.44 for the C50 concrete. The concrete was prepared in an inclined axis mixer at the Civil Engineering Laboratories, Unipampa (Alegrete Campus), Brazil.

The test samples were cast in the 10 cm cubic forms made of wood shown in Figure 1a, in which they remained during 24 hours before being removed from the forms (Figure 1b) and transferred to a chamber with controlled temperature ($23\pm1^{\circ}\text{C}$) and relative humidity (above 95%), where they remained 28 days until testing.

Table 1: Composition of mixes employed in the study.

MATERIAL	C30	C50
Portland Cement [kg/m ³]	319.1	454.1
Sand [kg/m ³]	820.2	921.2
Coarse aggregate with $d_{\text{max}}=19\text{mm}$ [kg/m ³]	1113.7	1049.0
Water [kg/m ³]	217.0	199.8
Superplastifyer [kg/m ³]	-	1.09
Specific mass [kg/m ³]	2444.6	2470.1
Slump [cm]	140	110

The upper face of the cubic samples during casting and curing was identified with a 0° sign, while one of the *lateral* faces (in relation to the orientation of casting) was identified with the 90° sign.

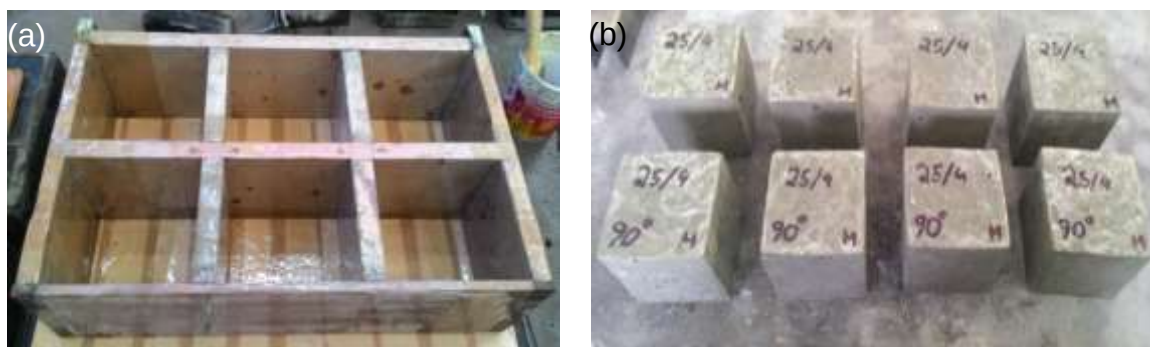


Figure 1: (a) wood forms employed in samples preparation; (b) view of samples after removal from the forms.

Six samples of each concrete type were tested after 28 days, both in the orientation of concrete casting (vertical direction) and in a direction normal to the direction of casting in a uniaxial testing machine (EMIC model PC150C) provided with a loading cell with a 1.5 MN capacity, shown in Figure 2a. Examples of tested samples may be seen in Figures 2b and 2c.



Figure 2 (a) Uniaxial testing machine Emic / PC150C, (b and c) view of tested sample at times t_i e t_f .

3. RESULTS

This section presents the results of compression tests of standard reference samples, as well as the compressive strengths measured in cubic samples in the direction of casting and in an orthogonal perpendicular to this direction.

3.1 STANDARD COMPRESSION TESTS

To complete the characterization of the two concrete types tested, the stress-strain curves of mixes C30 and C50 were determined by means of standard unconfined compression tests in an INSTRON Universal Testing machine, Model 5590 HLV Series, with 1.5 MN capacity. The displacement sensors of the instrument have a sensibility of 0.001mm. The resulting stress-strain curves are shown in Figure 3, from which Young's modulus of concretes C30 and C50 in unconfined compression may be determined, resulting in $E_{30} = 31.4$ GPa and $E_{50} = 35.6$ GPa, respectively.

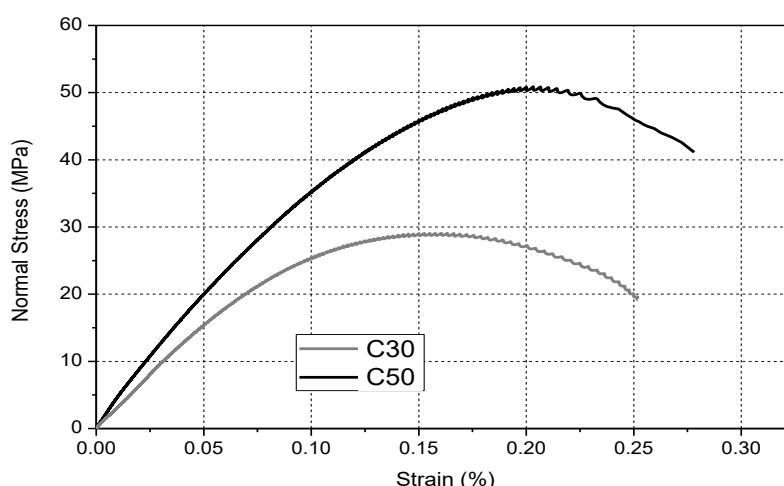


Figure 3: Stress vs. strain curves for concretes C30 and C50 in standard compression tests.

3.2 COMPRESSIVE STRENGTH OF CUBES

The twelve 10 cm cubic samples sets of two concrete mixtures C30 and C50 were tested after 28 days in two groups (a) with the compression load applied in the direction of concrete casting (vertical orientation) and (b) with the load applied in one of the lateral directions (horizontal orientation). Thus, for each nominal concrete strength, six samples were tested in

the upright position (a) and another set of six samples were tested in a horizontal direction (b). Table 2 shows the rupture configurations and measured strengths of the samples of 30MPa and 50MPa concrete. Mean, standard deviation and coefficient of variation (CV) for each set are also shown.

Table 2: Compressive strength of cubes of both concrete types in the orientation of casting and in a lateral (horizontal) orientation.

C30				C50			
Vertical direction		Horizontal direction		Vertical direction		Horizontal direction	
	σ MPa		σ MPa		σ MPa		σ MPa
	35.61		30.55		59.07		43.25
	31.62		38.47		55.77		44.02
	38.67		34.42		39.61		50.07
	36.03		39.56		52.30		45.34
	39.16		37.93		54.00		44.54
	40.73		36.68		55.61		39.58
σ_{mean}	36.97	σ_{mean}	36.27	σ_{mean}	52.73	σ_{mean}	44.47
Standard deviation	3.26	Standard deviation	3.31	Standard deviation	6.81	Standard deviation	3.40
CV (%)	8.82	CV (%)	9.12	CV (%)	12.91	CV (%)	7.64

Denoting as η the ratio between the horizontal and vertical compressive strengths, it follows that the expected value of η for both concretes may be estimated as:

$$E(\eta_{30}) \approx 36.27 / 36.97 = 0.9810$$

$$E(\eta_{50}) \approx 44.47 / 52.73 = 0.8433$$

Note that for the C30 concrete, the 80% confidence intervals for the compressive strengths in the direction of casting (vertical) and in a horizontal direction are:

$$36.97 \pm 1.282 \times 3.26 / \sqrt{6} = [35.27, 38.67]$$

$$36.27 \pm 1.282 \times 3.31 / \sqrt{6} = [34.57, 37.97]$$

Since there is overlapping, it is concluded that the horizontal strength is only marginally smaller, as may be inferred from the $E(\eta_{30})$ value, which is slightly smaller than 1. For the C50 concrete, however, the 80% confidence intervals for the compressive strengths in the direction of casting (vertical) and in a horizontal direction are:

$$52.73 \pm 1.282 \times 6.81 / \sqrt{6} = [49.12, 56.33]$$

$$44.47 \pm 1.282 \times 3.40 / \sqrt{6} = [42.67, 46.27]$$

Since there is no overlapping between confidence intervals, it is judged that the difference between the uniaxial compressive strengths in the vertical and any horizontal direction is significant above an 80% confidence level. This result suggests, in consequence, that the difference between vertical and horizontal unconfined strengths of concrete increases with the mean strength, which would be compatible with the notion that *horizontal initial micro-fractures* under the coarse aggregate are responsible for the lower strength in horizontal directions. The ratio between these gravity caused cracks and the total number of cracks or imperfections should decrease as the latter increases, that is, with the quality of concrete. Moreover, the significance of this effect, herein determined on cubic samples in conventional tests, should estimate a lower bound of the difference between vertical and horizontal strengths, because the effect should be more pronounced *when the failure configuration consists of*

vertical fractures. Such failure pattern was rarely observed in the experiments due to friction at the upper and lower loading platens.

4. CONCLUSIONS

There is extensive evidence in the technical literature that the unconfined compressive strength of conventional concrete, measured in cylindrical samples *extracted from built structures*, oriented *in situ* in the vertical direction, is up to about 10% higher than the strength measured in samples oriented *in situ* in a horizontal direction. In spite of the evidence, in engineering structural analysis and design, concrete is normally assumed isotropic, simplification that may usually be justified by practical considerations. The effect was also observed in cubes of two concrete types subjected to unconfined compression in the direction of concrete casting (vertical) and in a horizontal direction, within a pilot experimental study with results reported herein. No similar evidence obtained in laboratory studies was found in the open technical literature. These initial studies provide strong support to existing physical explanations of the causes of the anisotropy under consideration, suggesting moreover that the effect may result in errors of the order of 10% in the estimated carrying capacity of reinforced concrete components, deserving in consequence additional research. For obvious reasons, the relevance of the subject increases in case of prefabricated elements, which are often cast in a position that does not coincide with its location in the final structure.

ACKNOWLEDGMENTS

The authors acknowledge the financial support of FAPERGS, CNPq and CAPES.

REFERENCES

- AASHTO T124 (2005): "Methods of sampling and testing: obtaining and testing drilled concrete cores", USA.
- Hughes BP and Ash JE (1970) Anisotropy and failure criteria for concrete. *Matériaux et Construction*. Volume 3, Issue 6, pp 371–374.
- Neville, A. M. (1996): *Properties of Concrete*, 4th ed., John Wiley & Sons, Inc., New York, USA.

- Ozyildirim, C. and Carino, N.J. (2010): Chapter 13. Concrete Strength Testing, ASTM STP169D, Significance of Tests and Properties of Concrete & Concrete-Making Materials, Lamond, J.F. and Pielert, J.H.(Editors), PA, USA.
- Riera, J.D., Miguel, L.F.F., and Iturrioz, I. (2017): “Material models in applications of the Discrete Element Method (DEM) to 3D concrete compression”, Transactions, SMiRT-24, 24th Conference on Structural Mechanics in Reactor Technology, BEXCO, Busan, Korea - August 20-25, 2017.
- Suprenant, B. A. (1985): “An Introduction to Concrete Core Testing”, *Civil Engineering for Practicing and Design Engineers*, Vol. 4, No. 8, 1985, pp. 607–615.