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Scatter of Constitutive Models of the Mechanical Properties of Concrete: Comparison of Major International Codes

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Abstract

An investigation on the scatter of code-type constitutive models that relate compressive strength (f_c) with tensile strength (f_{ct}) and Young's modulus (E_c) of standard concrete specimens is presented. The influence of the mix design on the accuracy of the f_c *vs.* f_{ct} and f_c *vs.* E_c relationships is discussed, with emphasis on the lithological type and morphology of the coarse aggregates. The uncertainty of the constitutive models is analysed in probabilistic terms and random variables that model the uncertainty of the f_c *vs.* f_{ct} and f_c *vs.* E_c relationships are proposed for reliability analyses of serviceability limit states. The suitability of the models proposed is assessed through preliminary conservative estimates of their design values.

1. Introduction

Concrete codes and standards of quality control are mostly concerned with concrete's compressive strength (f_c). The other properties are usually estimated through constitutive models. Since codes are developed with emphasis on applicability, the same constitutive models are used for concrete produced with very different materials and mix design when in fact differences in constitutive relationships may be significant. This is a particularly relevant fact since in most construction works only f_c is tested and the other concrete properties may never be known.

This paper analyses the model uncertainty (θ) of the constitutive relationships between f_c and Young's modulus (E_c) and between f_c and tensile strength (f_{ct}) in different documents. Equation (1) illustrates the concept of θ for E_c .

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$$\theta_E = \frac{Experimental\ E_c}{Constitutive\ \mathrm{mod}\,el\ estimate\ of\ E_c} \quad (1)$$

If the model uncertainties of E_c (θ_E) and/or of f_{ct} (θ_{fct}) significantly change, this means that some concrete mix designs will result in structures with serviceability and ultimate limit-states behaviour that may differ from that foreseen by the codes.

Concrete technology has been developing steadily over the last decades and the advent of new types of concrete increased the range of concrete mixes used. The same concrete codes are applicable to mixes with very different admixtures, binder blends, and specified f_c . Materials such as superplasticizers and waste materials (silica fume - SF, recycled aggregates, fly ash - FA, ground granulated blast-furnace slag - GGBS, and others) are becoming increasingly popular and their influence on concrete and cement paste properties affects the microstructure and behaviour of concrete, influencing the constitutive relationships (Alexander and Milne 1995; Bravo *et al*. 2015b; Saito and Kawamura 1989). The incorporation of FA and GGBS is noteworthy: most concrete produced in developed countries nowadays includes either of these materials, but the constitutive models of codes treat these types of concrete (and all others) in the same way as concrete with ordinary Portland cement (OPC) blend.

2. Reesearch goals and significance

This paper intends to investigate whether different mix designs and strength ranges will result in different accuracy and precision of the θ of the f_c *vs* f_{ct} and f_c *vs.* E_c relationships. The main objective of the paper is the proposal of probability distributions of θ_E and θ_{fct} intended for serviceability limit-state (SLS) reliability analyses.

Coefficients θ_E and θ_{fct} are calculated as shown in

Table 1 Constitutive models.

Tensile strength:		
Eurocode 2 (2008) and Model Code 2010	$f_{ctm} = 0.30(f_{cm} - 8)^{2/3}$ if strength class $\leq C50$ $f_{ctm} = 2.12 \ln\{(1 + f_{cm}/10)\}$ if strength class $> C50$	(2)
Eurocode 2 (2020)	$f_{ctm} = 0.30(f_{cm} - 8)^{2/3}$ if strength class $\leq C50$ $f_{ctm} = 1.10(f_{cm} - 8)^{1/3}$ if strength class $> C50$	(3)
ACI 318	$f_{ctm,splt} = 0.56(f_{cm})^{1/2}$	(4)
Young's modulus:		
Eurocode 2 (2008)	$E_{cm} = \alpha 22000\{f_{cm}/10\}^{0.3}$	(5)
Model Code 2010	$E_{cm} = \alpha 21500\{f_{cm}/10\}^{1/3}$	(6)
Eurocode 2 (2020)	$E_{cm} = \alpha 10000 f_{cm}{}^{1/3}$	(7)
ACI 318	$E_{cm} = 4700(f_{cm})^{1/2}$	(8)

Equation (1) from 28-day test data from several publications and mix designs and probabilistic models are then developed for both θ_E and θ_{fct}.

Current SLS reliability analyses are hindered since the only concrete property specified in common construction projects is the characteristic compressive strength (f_{ck}) and most SLS are related to crack or deflection control. The actual E_c and f_{ct} are quite uncertain. Since probabilistic conversion models from expected to actual properties are lacking - the only study on this subject known to the authors dates from 1979 (Mirza *et al*. 1979), publications on the reliability of the SLS of concrete (Honfi *et al*. 2012) neglect this source of uncertainty with obvious consequences on the estimates of the probabilities of failure of SLS. This is a very relevant absence in the state-of-the-art of structural concrete and hinders, for instance, the reliability-based calibration of SLS code verifications.

The ultimate goals of the paper are:

1. Quantification of the statistics of θ_E and θ_{fct} of codes;
2. Analysis of the influence of different mix designs on θ_E and θ_{fct}, with emphasis on the coarse aggregates used, including recycled concrete aggregates;
3. Development of probabilistic models for θ_E and θ_{fct}, intended for reliability analyses related to the deflections and cracking calculations of SLS.

The relationships analysed are those of ACI 318 (2014), the current version of Eurocode 2 (2008), Model Code 2010 (*fib* 2010), and the October 2017 draft of the Eurocode 2 revision with expected publication in 2020, herein named Eurocode 2 (2020).

The mechanical properties of concrete are frequently tested in ϕ 100 mm x 200 mm cylinders instead of in the cylinder size of standards (ϕ 150 mm x 300 mm). Since some standards (ASTM-C31M 2003) treat the f_c of ϕ 100 mm x 200 mm cylinders as if ϕ 150 mm x 300 mm had been tested, θ is analysed for both cylinder sizes and the applicability of constitutive models with f_c data coming from ϕ 100 mm x 200 mm cylinders is discussed.

Concrete is a highly complex and heterogeneous material that can be produced with very different materials and proportioning. This means that models that would predict the θ_E and θ_{fct} accurately are not possible. The aim of the paper is the definition of suitable models that estimate θ_E and θ_{fct} within a reasonable margin and within the scope of serviceability reliability analyses. As stated in codes, if E_c and/or f_{ct} are important in ultimate limit state design, specific testing should be made.

Also because of the variability in concrete mix design, the specific influence of aggregate type (or other parameters) cannot be fully accounted for, since the concrete mix design of each individual study is biased towards the regional practice and materials of the laboratory were that study was made. Research concerning the influence of specific parameters (such as strength class, binder blend, and type of aggregate) on the constitutive models of concrete should be analysed through individual laboratory tests, were the other mix design parameters can be kept constant.

3. Methodology

3.1 Code-type models

Equations (2) - (8) are written in **Table 1** and show the constitutive models analysed. A notations table, provided in a separate section of the paper, states the meanings of each symbol. All units are in MPa. The models of Model Code 2010 and both Eurocode versions are very similar.

The α factor of Equations (5) – (7) depends on the nature of the aggregates: 1.0 for quartzite aggregates, 1.2 for basalt, 0.7 for sandstone, and 0.9 for limestone aggregates. Since current codes have no clauses for recycled aggregate concrete properties, recycled concrete aggregate was analysed with an α factor of 0.7, as argued for by Silva *et al*. (2016). Since the objective of the paper is determining the accuracy of the θ of codes, rather than proposing new code-type models, the α factors will be used as specified in codes even if more suitable values could be found. The formula of ACI 318

(2014) has no α factor and does not account for the type of aggregate.

References to the characteristic compressive strength (f_{ck}) were converted to the average compressive strength (f_{cm}) in Equations (2) – (3). As specifically recommended in Eurocode 2 (2008), Eurocode 2 (2020), and Model Code 2010, f_{cm} was considered as $f_{cK}+8$ MPa.

Equation (4) concerns the splitting tensile strength, whilst Equations (2) – (3) estimate the uniaxial f_{ct}. All experimental data appraised on the paper concern splitting tensile strength tests and the θ_{fct} analysis will be made as if splitting tensile strength data were equivalent to those of uniaxial f_{ct}. This option was made because splitting tensile tests are by far the most common type of experimental test on f_{ct}. Conceptually, the uniaxial tensile strength is a more correct test, but is highly sensitive to the experimental setup and heterogeneities of specimens (Bažant and Cedolin 1993). Malárics and Muller (2010) performed extensive research and argue in favour of converting splitting tensile strength data into uniaxial f_{ct} data using a factor of 1.0. Model Code 2010 also follows this recommendation (*fib* 2013).

3.2 Types of analysis

θ_E and θ_{fct} in the constitutive models of the four documents are calculated using Equations (2) – (8) for each concrete mix appraised and the following analyses are made:

1. Influence of the aggregate type on the statistics of θ_E;
2. Influence of the aggregate morphology on the statistics of θ_{fct};
3. Influence of f_c on θ_E and θ_{fct};
4. Goodness-of-fit testing of lognormal and normal distributions for θ_E and θ_{fct};
5. Definition of suitable probability distributions for θ_E and θ_{fct};
6. Assessment of the errors of the proposed probability distributions in comparison to the actual data within an SLS framework.

The type of the coarse aggregate is arguably the most relevant parameter that determines the f_c *vs.* E_c relationship (Alexander 1996; *fib* 2013; Kliszczewicz and Ajdukiewicz 2002). Limestone (LS), sandstone (SS), basalt (BS), granite (GR), quartzite (QZ), and recycled concrete aggregates (RA) were analysed. The five types of natural aggregates are the most commonly used aggregates in concrete technology, whilst RA are the most common type of recycled aggregates. The incorporation of RA affects θ_E since its high deformability has a more relevant effect on E than on f_c (Silva *et al*. 2016).

Coefficient θ_{fct} is analysed in terms of three coarse aggregate morphologies: crushed natural aggregates (CNA), rounded natural aggregates (RNA), and crushed recycled aggregates (CRA). These aggregate morphologies result in different interfacial transition zones (ITZ) between the coarse aggregates and the cementitious paste (*fib* 2013; Sidorova *et al*. 2014).

The specified strength class may influence θ_E and θ_{fct} since f_c increases are related to stiffer and stronger cement pastes, which increases the dependence of E_c and f_{ct} on aggregate characteristics (Bravo *et al*. 2017; *fib* 2008). Within the high-strength concrete range (f_c above 50 MPa), the deformability of the cementitious paste becomes similar to that of the aggregates and a relevant number of trans-aggregate fractures occur on the failure surface of specimens (*fib* 2013).

Admixtures influence the microstructural properties of concrete, particularly in the ITZ region (Saito and Kawamura 1989), and they are expected to affect both the θ_E and θ_{fct} relationships (Mehta and Monteiro 2006).

Because of the dependence of the f_c *vs*. f_{ct} and f_c *vs*. E_c relationships on all these factors, the statistics of θ_E and θ_{fct} are analysed by subpopulations split by strength range and aggregate lithology/morphology. Scatterplots that show the blinder blend of each mix are also plotted and considered in the analysis. The relevance of each subpopulation is judged considering its particular mix designs.

3.3 Database criteria

Data were appraised from publications in which f_c, E_c and/or f_{ct} were obtained from the same concrete batch. Data from cylinders of different size (either ϕ 150 x 300 mm or ϕ 100 x 200 mm) were not mixed and conversions from experiments on specimens with other dimensions were not made since such conversions are highly scattered and dependent on the type of coarse aggregate used (Pacheco *et al*. 2019b). All data concern tests performed at 28 days.

Mixes with RA enhanced by beneficiation techniques were not included in the database. Only RA concrete with total RA incorporation was analysed, since data on intermediate replacements of natural aggregates by RA are not as numerous. Some references concern properties of concrete exposed to high temperatures but only tests on control specimens subjected to normal temperatures were analysed.

Self-compacting concrete mixes were not collected since this type of concrete is associated with binder contents, w/b ratios, and binder blends that differ from traditional concrete mix design. Since self-compacting concrete is specified during design, specific models for its θ relationships should be developed separately and used explicitly when analysing the behaviour of self-compacting concrete.

Figures 1 and **2** show the distribution of concrete mixes by aggregate nature (E_c) and aggregate morphology (f_{ct}).

The sources of the f_c *vs.* E_c data were the following:

- ϕ 150 mm cylinders: Ajdukiewicz and Kliszczewicz (2002, 2007), Atahan *et al*. (2011), Bilodeau and Malhotra (1992), Bravo *et al*.

(2015a), Carette *et al.* (1993), Casuccio *et al.* (2008), Demir (2009), Dilbas *et al.* (2014), Dossey *et al.* (1994), Etxeberria *et al.* (2007a-b), Evangelista (2014), Evangelista and de Brito (2017), Gomez-Soberon (2002), González-Fonteboa and Martínez-Abella (2004, 2005), González-Fonteboa *et al.* (2011), Gutierrez and Canovas (1995), Hamad and Dawi (2017), Kheder and Al-Windaw (2005), Kliszczewicz and Ajdukiewicz (2002), Koulouris *et al.* (2004), Naik *et al.* (1998), Omary *et al.* (2018), Paul (2011), Pedro *et al.* (2014), Piasta *et al.* (2017), Pul (2008), Remesar *et al.* (2017), Sadati and Khayat (2016), Sivasundaram *et al.* (1989, 1991), Tufail *et al.* (2017), Zega and Di Maio (2006, 2009);

- ϕ 100 mm cylinders: Aitcin and Mehta (1990), Akcay *et al.* (2012), Aksut and Yetgin (2017), Arezoumandi *et al.* (2015a-b), Bordelon *et al.* (2009), Butler (2012), Butler *et al.* (2013), Cetin and Carrasquillo (1998), Chang *et al.* (2001), Choi *et al.* (2012), Cülfik and Özturan (2010), Donza *et al.* (2002), Freyne *et al.* (2004), Gholampour and Ozbakkaloglu (2017), Giaccio and Zerbino (1998), Gonzalez-Corominas and Etxeberria (2014), Gonzalez-Corominas *et al.* (2017), Huang *et al.* (2013), Huda and Alam (2014), Iravani (1996), Jin and Li (2003), Khaliq and Taimur (2018), Kim *et al.* (2002), Kou *et al.* (2007), Lee and Yoon (2015), Manzi *et al.* (2013), Mesbah *et al.* (2002), Ozbakkaloglu *et al.* (2018), Park *et al.* (2013), Pepe (2015), Razaqpur *et al.* (2010), Sadati and Khayat (2016), Tasdemir and Karihaloo (2001), Teranishi *et al.* (1998), Tibbetts *et al.* (2018), Vogel and Svecova (2012), Yanagi *et al.* (1998), Yang *et al.* (2008), Yiğiter *et al.* (2007), Yoshitake *et al.* (2014).

The sources of the f_c *vs.* f_{ct} data were:

- ϕ 150 mm cylinders: Ajdukiewicz and Kliszczewicz (2002, 2007), Alonso *et al.* (2002), Ashour (2000), Bakhsh *et al.* (1990), Bravo *et al.* (2015a), Demir (2009), Dossey *et al.* (1994), Etxeberria *et al.* (2007a-b), Evangelista (2014), Evangelista and de Brito (2017), Oluokun *et al.* (1991), Gardner (1990), Gardner *et al.* (1988), Gerges *et al.* (2015), Giaccio and Zerbino (1998), Gomez-Soberon (2002), González-Fonteboa and Martínez-Abella (2004, 2005), González-Fonteboa *et al.* (2011), Gupta *et al.* (2016), Hamad and Dawi (2017), Kliszczewicz and Ajdukiewicz (2002), Muhammad and Sankaranarayanan (2016), Naik *et al.* (1998), Omary *et al.* (2018), Pedro *et al.* (2014), Proske *et al.* (2014), Pul (2008), Sadati and Khayat (2016), Saouma *et al.* (1991), Sivasundaram *et al.* (1989), Tufail *et al.* (2017), Yagishita *et al.* (1993), Zega and Di Maio (2011);
- ϕ 100 mm cylinders: Adams *et al.* (2016), Aksut and Yetgin (2017), Amario *et al.* (2017), Andal *et al.* (2016), Arezoumandi *et al.* (2014, 2015a-b), Bordelon *et al.* (2009), Butler (2012), Butler *et al.* (2013), Chang *et al.* (2001), Cülfik and Özturan (2010), Durán-Herrera *et al.* (2011), Becker and Javier (2018), Freyne *et al.* (2004), Gholampour and Ozbakkaloglu (2017, 2018), Giaccio and Zerbino (1998), Gonzalez-Corominas and Etxeberria (2014), Gonzalez-Corominas *et al.* (2017), Kang *et al.* (2014), Khaliq and Taimur (2018), Khan-

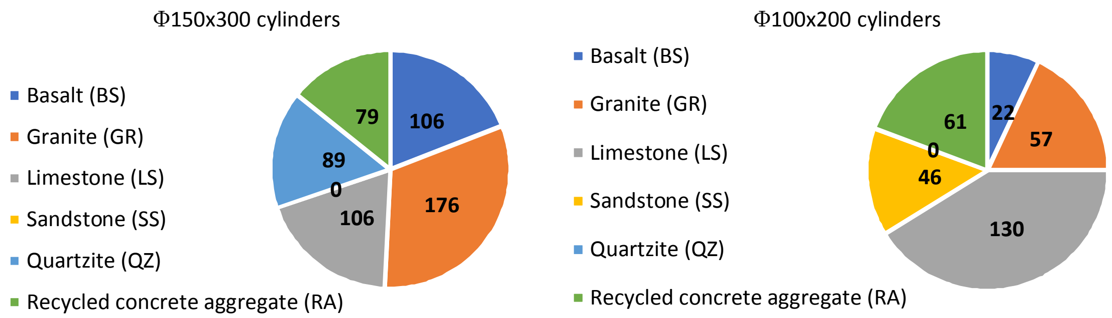


Fig. 1 Number of mixes of each aggregate type - θ_E database.

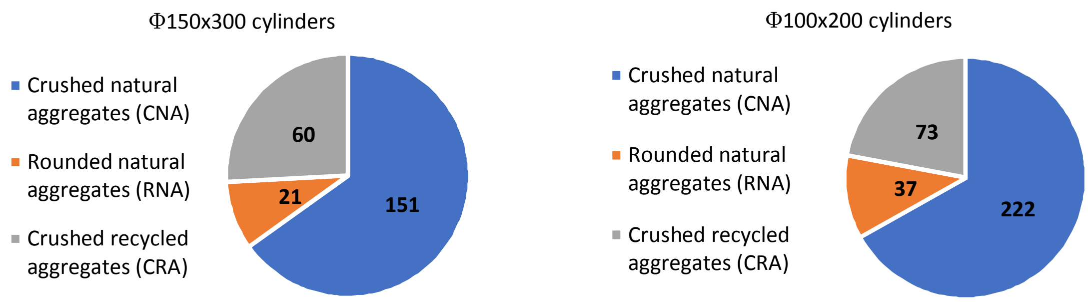


Fig. 2 Number of mixes of each aggregate morphology - θ_{fct} database.

zadi and Behnood (2009), Kim *et al*. (2002, 2013, 2016), Kou and Poon (2015), Kou *et al*. (2007), Lam *et al*. (1998), Laneyrie *et al*. (2016), Lee and Yoon (2015), Lotfy and Al-Fayez (2015), Manzi *et al*. (2013), Mohammed *et al.* (2017), Mouret *et al*. (1997), Naik *et al.* (2011), Park *et al*. (2013), Pepe (2015), Sadati and Khayat (2016), Soleymani Ashtiani *et al*. (2013), Tangchirapat *et al.* (2013), Uzal *et al.* (2007), Yang *et al.* (2008), Yiğiter *et al*. (2007), Yildirim *et al*. (2015), Yoshitake *et al*. (2013, 2014).

Most of the data concern crushed LS. This was expected due to the representativity of LS aggregates in the concrete industry. The analysis of the f_c *vs*. f_{ct} relationship of RNA was limited by the reduced number of studies and mixes found.

The datasets divided by f_c range are detailed in the tables of the Appendix. The number of mixes and the main statistical descriptors of each dataset are also shown there. The tables of the Appendix show the maximum percentage of mixes from each population that were sourced from the same investigation. Datasets that are excessively dependent on a particular investigation are not ideal since the θ models will be dependent on the particular mix design, materials, and equipment used in that research. This was considered during the analysis of the results.

E subpopulations with SS aggregates were studied for ϕ 100 mm cylinders only due to scarce data on ϕ 150 mm cylinders. For the same reason, QZ aggregate concrete was analysed for ϕ 150 mm specimens only.

4. Young's modulus

4.1 General analysis of trends and code accuracy

Figure 3 shows the f_c *vs.* E_c scatterplots of all concrete produced with all aggregate types and both cylinder sizes.

Some trends are reported:

1. The relationship of ACI 318 differs from that of the other codes, especially in the low strength range;
2. The relationships of Model Code 2010 and Eurocode 2 (2020) are practically the same;
3. The θ_E of all standards is dependent on aggregate type. The α factor used in both Eurocode versions and Model Code 2010 does not reduce the influence of aggregate type on θ_E;
4. From these data, the α factor of concrete with GR seems too high and the α factor of LS aggregates too low;
5. The θ_E of ϕ 100 mm cylinders and of ϕ 150 mm cylinders are similarly scattered;
6. The E_c of RA concrete is underestimated by both Eurocode versions and Model Code 2010 when an α factor of 0.7 is used. However, since RA concrete is a new structural material with few full-scale applications (Pacheco *et al*. 2015), underestimating its properties until proven applications by the construction industry is usually a cautious option.

The datasets of the different types of aggregates differ in mix design, binder blends and f_c, since the data appraised came from several institutions and regions. A fair comparison between types of aggregate requires an analysis by strength intervals, as well as the consideration of the binder blends used. The next section of the paper deals with this aspect.

Since the analysis of the f_c *vs.* E_c models of Eurocode 2 (2008), Eurocode 2 (2020), and Model Code 2010 is quite similar, the discussion will mostly focus on Eurocode 2 (2008) and ACI 318. The same option was made when presenting the analysis of f_c *vs.* f_{ct}. The Appendix has the results of all codes.

4.2 Analysis by datasets

Figure 4 plots the θ_E of GR and RA concrete when Eurocode 2 (2008) relationships are used. The percentage of cement replacement with other materials and the cylinder size of the data are also provided.

It is clear that different strength intervals are biased towards particular binder blends (for instance OPC for lower strength ranges and SF for high-strength concrete). This means that the influence of binder blends and f_c on θ_E cannot be analysed separately. The θ_E analyses are made by checking the specific statistics of each strength interval and type of aggregate and assuming that the mix designs of the data appraised are representative of concrete of that strength interval. When unexpected trends were found, the particular mix designs of those datasets are analysed.

The statistics analysed were the average and coefficient of variation (CoV) of θ_E since the sample standard deviation was found to be more dependent on f_c than the CoV. The Appendix presents the standard deviation, as well as the skewness and kurtosis of each dataset.

Figure 5 shows the average and CoV of θ_E off all aggregate types calculated using the relationship of Eurocode 2 (2008).

Some trends are found:

1. In most cases, the average θ_E of ϕ 150 mm cylinders is higher than the θ_E of ϕ 100 mm cylinders. This is explained by the physical phenomena behind statistical and fracture mechanics size effects (Bažant and Yavari 2005): f_c tends to decrease with increases in specimen size both due to:
   - Increased probability of finding weak zones in materials (statistical size effects);
   - For the same stress, the elastic energy stored in a specimen increases with its size. On the other hand, failure develops in a region that is almost independent on the specimen size (fracture mechanics size effects), i.e. the elastic energy released after cracking is higher in larger specimens.

   When E_c is tested, fracture mechanics' size effects are not as relevant, since the stresses on the specimen are well below f_c, therefore cracking is limited. Moreover, in E_c tests the average strain of a significant portion of the specimen is measured, so the effect of weak regions is averaged out and statistical size effects are reduced. Since f_c increases for smaller specimens but E_c is negligibly affected, codified f_c *vs.* E_c relationships developed from tests on ϕ 100 mm cylinders will underestimate E_c in comparison to relationships developed from tests on the standard cylinder size;

2. Cylinder size did not have a meaningful effect on the CoV of θ_E. By analyzing the sample sizes and the maximum percentage of mixes coming from the same paper (Appendix), as well as the particular mix designs of each set of data, it becomes clear that a scientifically-sound prediction of the variability of θ_E cannot be made. Nevertheless, a CoV of 12% suits the data well enough for SLS reliability purposes, as will be shown in section 4.4;
3. The α factor used in Equations (5) – (7) does not ensure similar code accuracy between aggregate types. For instance, the E_c of concrete with either LS or RA is underestimated by all codes except ACI 318. The reduction of the E_c of LS concrete in Eurocode

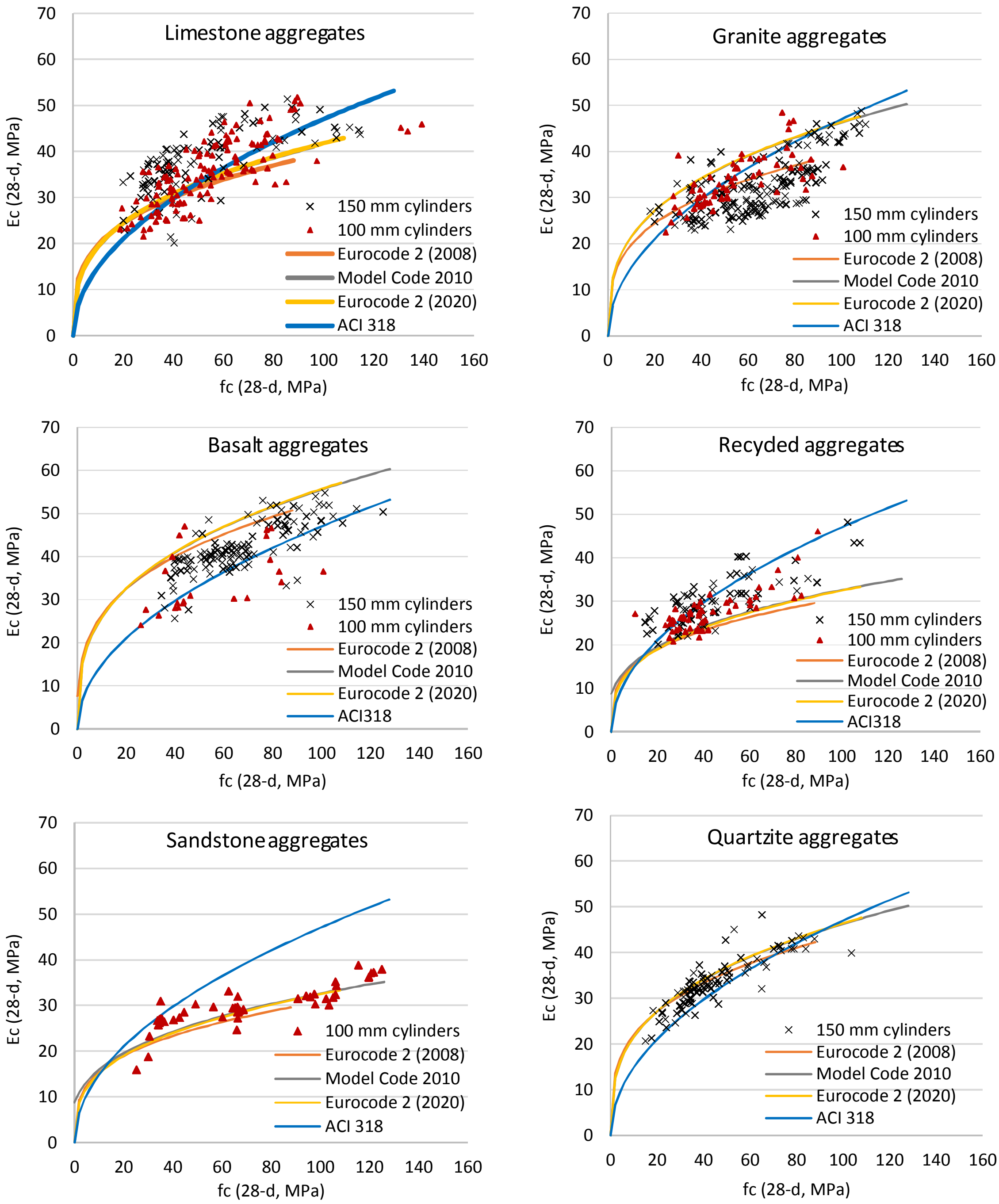


Fig. 3 f_c vs. E_c relationships.

2 (2008), Eurocode 2 (2020), and Model Code 2010 is not consensual. Noguchi *et al.* (2009) compiled data from several authors and found that LS concrete tends to have higher E_c than QZ and BS concrete. These contradictory findings in comparison to Eurocode 2 and Model Code 2010 must be related both with differences in the properties of stones coming from quarries of different regions and with the specific mix design and specimen geometries of the mixes tested in each investigation;

4. The f_c *vs.* E_c relationship of ACI 318 does not account for the type of aggregate but its θ_E is as dependent on the aggregate type as the θ_E of the other documents. This follows from the previous conclusion: even though Equations (5) – (7) use the α factor, a homogenous θ_E between aggregate types is not achieved. This finding has important consequences on the reliability of SLS that depend on concrete stiffness.

Some populations did not conform with the trends reported above. When specific datasets are analysed, reasons for such divergences are found. The average θ_E of GR concrete of ϕ 100 mm cylinders is higher than the average θ_E of ϕ 150 mm cylinders, especially in the 50 - 90 MPa f_c range. This is explained by the particular admixtures used and the age of testing (28 days). **Figure 4** shows that for f_c above 50 MPa:

- The ϕ 100 mm data of GR concrete concern mostly concrete with 10% to 25% of FA by total binder weight;
- The ϕ 100 mm data concern concrete with either OPC or OPC with 4% to 10% of SF;

All data come from specimens tested at the conventional age of 28 days. However, the pozzolanic reactions of FA are only noticeable several weeks after the onset of hydration (Langan 2002). At 28-days, the ITZ improvements caused by FA incorporation are not relevant and FA acts mostly as a filler, reducing porosity but hav-

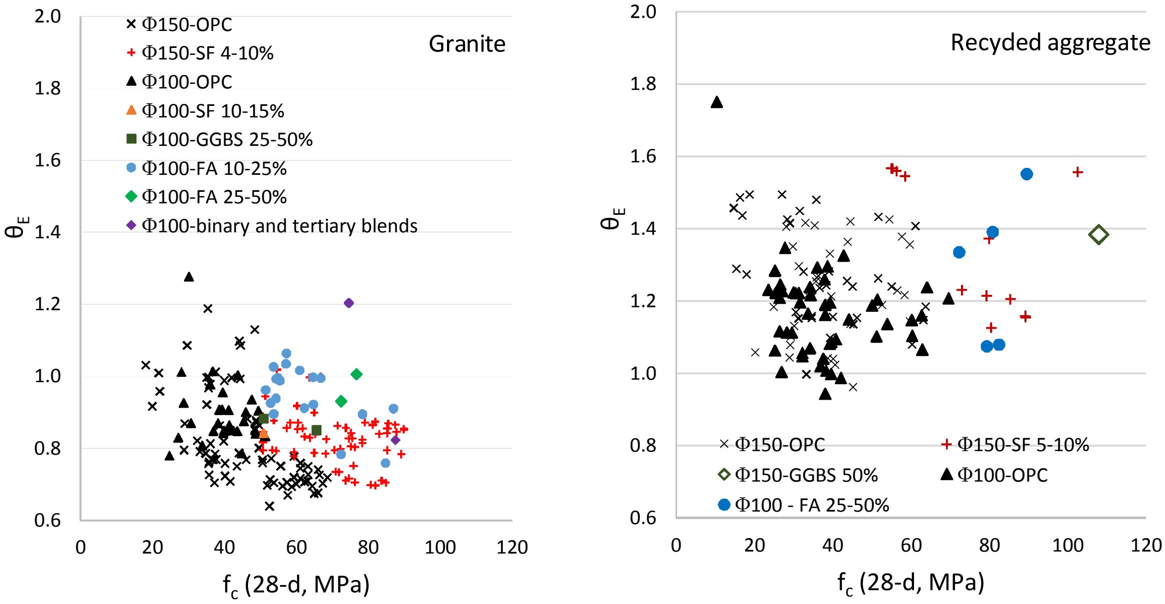


Fig. 4 f_{cm} vs. θ_E scatterplot of GR and RA concrete. Eurocode 2 (2008).

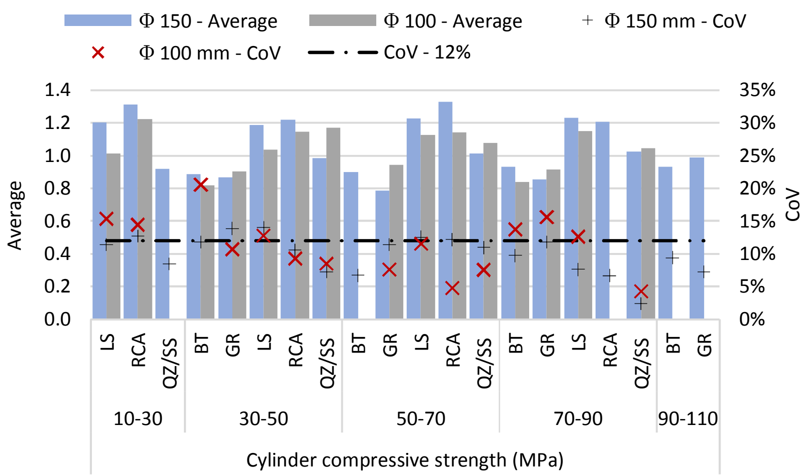


Fig. 5 Average and CoV of θ_E for each population. Eurocode 2 (2008).

Table 2 Average θ_E of the probabilistic models.

	Average θ_E for Φ 150 mm			CoV	Φ 100/Φ 150
Aggregate	Eurocode 2 (2008)	MC 2010 and Eurocode 2 (2020)	ACI 318	All codes	All codes
LS	1.20	1.15	1.15	12%	0.90
QZ	1.00	0.95	1.05	12%	-
BS	0.90	0.90	1.10	12%	-
GR	0.85	0.80	0.85	12%	0.90 (1.05)*
RA	1.20	1.20	0.90	12%	0.95

* The actual value is 1.05 but 0.90 is recommended conservatively (the specific binder blends of GR concrete may have conditioned its analysis)

ing little influence in crack arrest. This means that at 28 days FA will contribute more to E_c than to f_c, since E_c is tested under reduced stresses (30% to 40% of f_c) and crack propagation is not significant. Differerent authors have reported that concrete with FA has higher f_c gains over time in comparison to E_c (Marques *et al.* 2013, Pacheco *et al.* 2019a, Siddique 2004).

Relevant increases in θ_E when SF is used are not observed. SF is a highly reactive admixture and provides a significant amount of calcium silicate hydrates from the onset of hydration, contributing to early-age strength development (Langan 2002).

Noguchi *et al.* (2009) have also reported that FA incorporation skews the f_c vs. E_c relationships towards higher values of E_c, while SF does not have that effect.

4.3 Goodness-of-fit testing

All subpopulations were checked for lognormal and normal distribution fits. **Figure 6** plots the distributions of the subpopulations with compressive strength between 30 and 50 MPa, ϕ 150 mm cylinders, and with two types of coarse aggregates: RA (left) and LS (right).

Most of the distributions were suitably modelled by both normal and lognormal distributions. Some distributions could not be suitably modelled by either, but the purpose of these distributions (probabilistic models for SLS), allows normal and/or lognormal distributions:

- SLS have relatively high acceptable probabilities of failure: ISO2394 (1998) recommends probabilities of failure of about 7% for irreversible SLS and 50% for reversible SLS);
- The θ_E of constitutive models is one of the many resistance variables involved in the reliability of SLS. Assuming that θ is not the most relevant resistance variable (a fair assumption since the reliability of concrete elements under deformability verifications is expected to be more dependent on the statistics of the geometric parameters related to the inertia of cross-sections), θ_{Ed} is expected to be close to the average θ_E. From this follows that probability models with ill-fitted tails (**Fig. 6**, right) are not necessarily unsuitable within scope of SLS reliability analyses. This will be developed in the next section.

4.4 Proposed model for θ_E

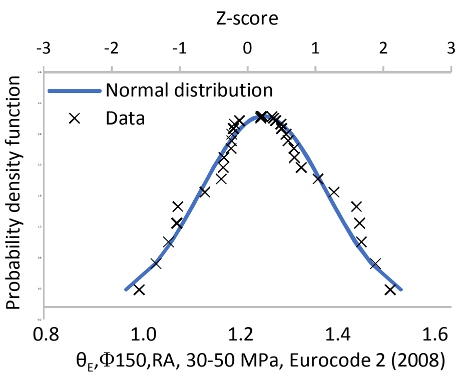
The probabilistic conversion model from code-predicted to actual E_c is defined by:

$$E_{c,actual} = \theta_E \times E_{c,code} \quad (9)$$

where θ_E is normally distributed with a CoV of 12% and the expected values are shown in **Table 2**.

This conversion is intended for ϕ 150 mm cylinders. If f_c tests on ϕ 100 mm cylinders are used, the expected value of θ_E should be multiplied by the ratio given in the same table. The CoV is independent of the cylinder size. Ratios for BS concrete were not developed due to insufficient sampling.

The expected value of θ_E of each aggregate type was defined by calculating the weighted average of the average θ_E of each strength range. This weighted average gave mixes within the 30 - 50 MPa and 50 - 70 MPa strength ranges three times more relevance in comparison to mixes of the respective 10 - 30 MPa, 70 - 90 MPa, and 90 - 110 MPa datasets (**Fig. 5** and the Appendix



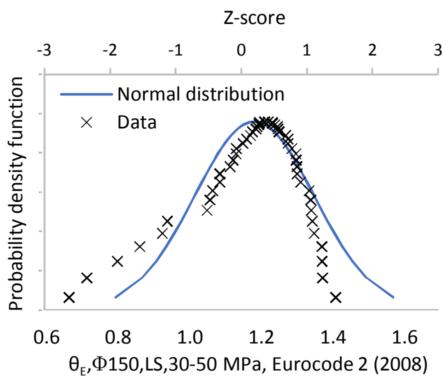


Fig. 6 θ_E normal distribution goodness-of-fit testing. Left): properly fitted data, right): unproperly fitted data but acceptable model.

Table 3 *Estimated* θ_{Ed}. Design service life of 50 years and a β of 1.5.

Aggregate	Eurocode 2 (2008)	MC 2010 and Eurocode 2 (2020)	ACI 318
LS	1.03	0.98	0.98
QZ	0.86	0.81	0.90
BS	0.77	0.77	0.94
GR	0.73	0.68	0.73
RA	1.03	1.03	0.77

show the averages of all datasets).

The ϕ 100/ϕ 150 ratio of GR concrete was higher than 1.0, a finding that lacks physical validity and was probably due to the specific mix design of the ϕ 100 mm cylinder GR mixes, as stated previously.

The same CoV (12%) is recommended for both cylinders' sizes and all types of aggregates of all codes since it suitably represents the CoV of most populations analysed. Cases that deviate significantly from the proposed CoV were analysed and correspond to populations that were mostly dependent on a single research.

The suitability of the models proposed in **Table 2** was checked by comparing the preliminary design (θ_{Ed}) values of the θ_E models with the preliminary θ_{Ed} calculated from each individual dataset. These preliminary θ_{Ed} were estimated using the clauses of Annex C of Eurocode 0 (2002), as shown in Equation (10):

$$\theta_{Ed} = Average\ (\theta_E) - \alpha_{R,FORM} \times \beta \times CoV \times Average\ (\theta_E) \quad (10)$$

where:

- β is the target reliability index recommended for irreversible SLS over a design service life of 50 years (β = 1.5, corresponding to a probability of failure of 7%);
- $\alpha_{R,FORM}$ is a conservative estimate of the sensitivity factor of a reliability analysis based on a first order reliability method (Madsen *et al.* 1986). Eurocode 0 recommends $\alpha_{R,FORM}$ = 0.8 for leading resistance variables.

Equation (10) assumes θ_E as normally distributed. Considering α_{FORM} = 0.8 is an overestimation of the effect of θ_E on reliability, since θ_E is not expected to be a leading resistance variable. Lower $\alpha_{R,FORM}$ values would result in θ_{Ed} closer to the average θ_E.

Table 3 shows the θ_{Ed} values obtained using the proposed models.

Figure 7 shows the Eurocode 2 (2020) and ACI 318 relative errors (Δ_{rel}) of the θ_{Ed} calculated with the proposed models and those of the datasets (assuming a normal distribution). Values above zero are conservative (underestimates of E_c). Model Code 2010 and Eurocode 2 (2020) statistics are fairly close to those of Eurocode 2 and can be observed in **Tables A.1** and **A.2** of the Appendix. The absolute errors (Δ_{abs}) are also in in **Tables A.1** and **A.2**.

Most of the errors of the models are conservative and the absolute value of Δ_{rel} is lower than 10% in almost all cases.

5. Tensile strength

5.1 General analysis of trends and code accuracy

The f_c *vs.* f_{ct} relationships of Eurocode 2 (2008) and ACI 318 are plotted in **Figs. 8 - 10**. Model Code 2010 and Eurocode 2 (2020) relationships are virtually the same as those of Eurocode 2 (2008). The 5% and 95% characteristic f_{ctk} estimates of Eurocode 2 (2008) are also plotted.

Figure 8 shows that the CNA concrete data are representative in all strength ranges. From **Fig. 9** it is concluded that data on RNA are lacking and **Fig. 10** shows that data on CRA concrete adequately cover the common strength classes.

Almost all data in the common strength classes of all aggregate morphologies concern concrete with plain OPC blends. High-strength concrete with CRA was made with either SF (3 - 10% of cement replacement) or FA (25 - 50%). Several binder blends were used in the high-strength concrete produced with CNA. The few RNA concrete mixes with high f_c were produced mainly with FA (25 - 50% of cement replacement).

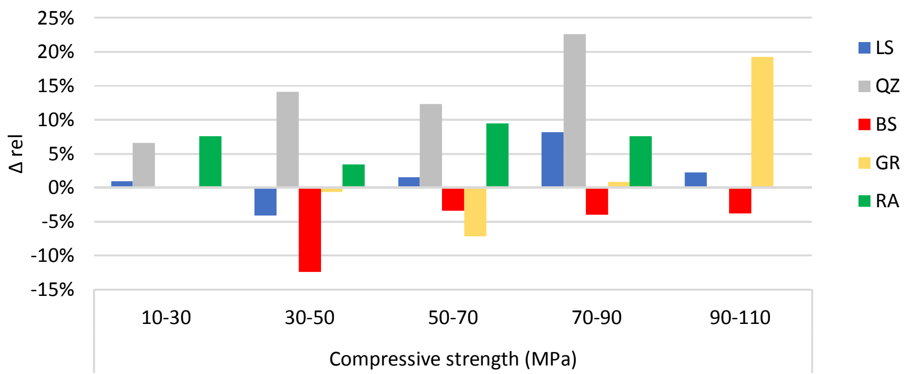


Fig. 7 Relative errors of θ_{Ed} when the proposed probability models are used.

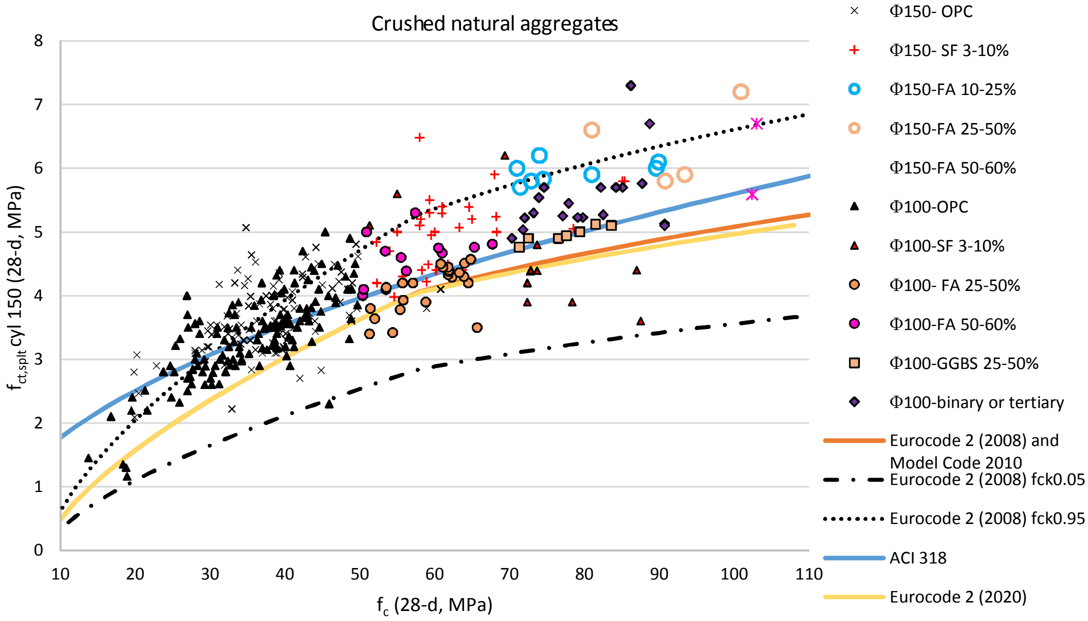


Fig. 8 f_c vs. f_{ct} relationships: CAN.

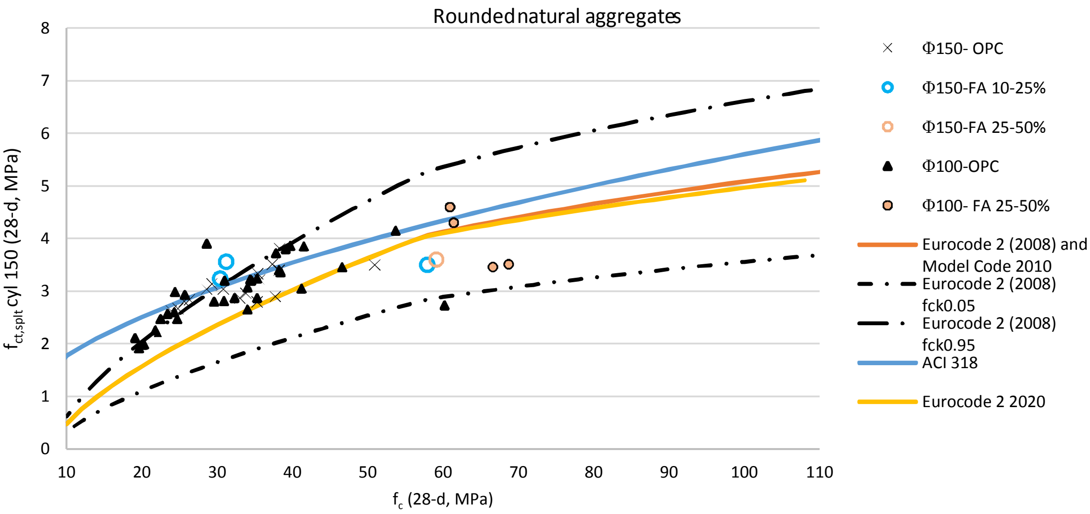


Fig. 9 f_c vs. f_{ct} relationships: RNA.

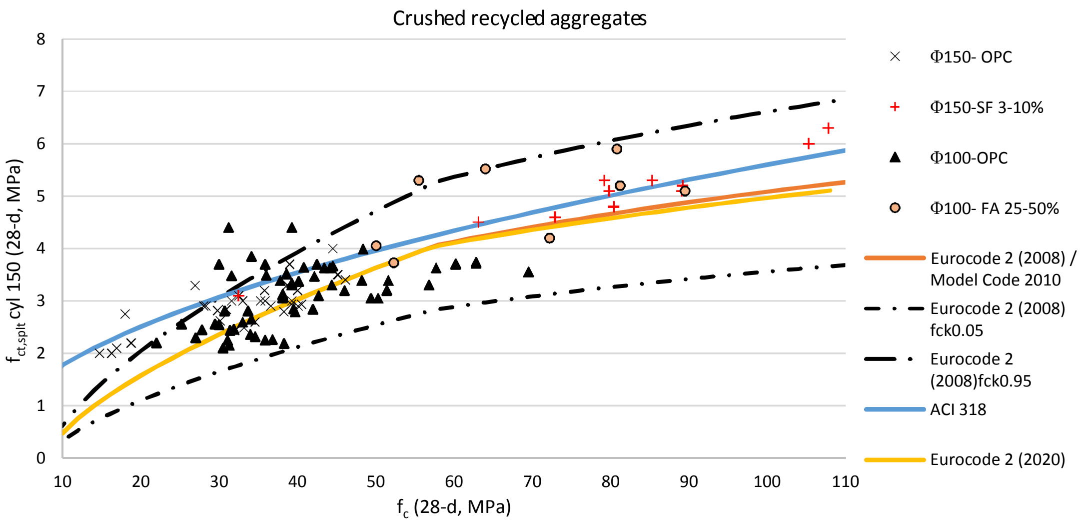


Fig. 10 f_c vs. f_{ct} relationships: CRA.

The following trends are observed:

1. Both versions of Eurocode 2 and Model Code 2010 predict almost the same f_{ct}. The predictions of ACI 318 are higher than all others;
2. Eurocode 2 and Model Code 2010 consistently underestimate the f_{ct} of CNA, especially in the lower strength range. The f_{ct} of RNA is also underestimated in the low to medium strength range;
3. The f_{ct} of CRA concrete is below expectations when the relationship of ACI 318 is used and underestimated by Eurocode 2 and Model Code 2010 in more instances than when concrete is produced with the other aggregate morphologies;
4. Almost all data of the three aggregate morphologies are above the 5% characteristic predictions of Eurocode 2 and Model Code 2010. The f_{ct} of CNA is clearly underestimated: 37% of the ϕ 150 mm data and 21% of the ϕ 100 mm cylinder data are above the 95% fractile estimate of f_{ct}.

The above conclusions assume that the splitting tensile strength is equal to the uniaxial f_{ct}. Malárics and Muller (2010) recommended a conversion factor of 1.0 but found that, in fact, the conversion factor depends on f_c and is greater than 1.0 for lower strength concrete. This justifies why most data above the prediction of the 95% fractile lie in the low to medium strength range.

5.2 Analysis of datasets

Figure 11 shows the average and CoV of θ_{fct} calculated using the Eurocode 2 (2008) and ACI 318 relationships. The θ_{fct} of the other documents are similar to that of Eurocode 2 (2008).

There is a slight trend towards ϕ 150 mm cylinders having higher average f_{ct} than ϕ 100 mm ones. This is because f_{ct} is almost size independent when the test setup has narrow load-bearing strips - as common in standards (*fib* 2013); Rocco *et al.* 1999a, 1999b), and the size of the cylindrical specimen is common (including ϕ 150 mm and ϕ 100 mm). Since f_c is not size independent, negligible f_{ct} size effects result in ϕ 100 mm cylinders having higher f_c and similar f_{ct} in comparison to the properties of standard cylinders. This means that f_c *vs.* f_{ct} relationships developed from tests on ϕ 100 mm cylinders will underestimate f_{ct} in comparison to the standard size of codes.

The reduced influence of specimen size on the f_{ct} may seem unexpected, since uniaxial tensile failures are more brittle than compressive failures (fib 2013, van Mier and Mechtcherine 2007). However, the failure mechanism of splitting tensile strength tests is very different from the mechanism of uniaxial tensile strength tests, which are characterized by the development of a few bridging cracks without potential for crack arresting (Mehta and Monteiro 2006). As Malárics and Müller (2010) have shown, splitting tensile strength specimens are subjected to a complex multiaxial stress-state, with a crack pattern that is dependent on the specimen's geometry, material properties and even the width of the load-bearing strips (Rocco *et al.* 1999a, 1999b), instead of being under uniaxial tension. This hinders intuitive deductions on the effect of specimen size on f_{ct}.

Some other findings are taken from **Fig. 11**:

1. ACI 318 predictions are fairly more accurate than all others, because the ACI 318 relationship estimates the splitting tensile strength and not the uniaxial f_{ct};
2. The average θ_{fct} of ACI 318 is homogenous for the different strength ranges, whilst the average θ_{fct} of the other documents decreases with f_c, which is probably due to the shift of the failure pattern towards trans-aggregate fractures. This is especially noticed when CRA are used, because CRA are weaker than natural aggregates (Guo *et al.* 2017);
3. The CoV from ϕ 100 mm data is more variable than that of ϕ 150 mm;
4. Concrete with RNA or CRA has lower θ_{fct} than CNA concrete. The f_{ct} of RNA concrete is limited by a weak ITZ (Arioglu *et al.* 2016) and the f_{ct} of CRA concrete is limited by aggregate strength (Casuccio *et*

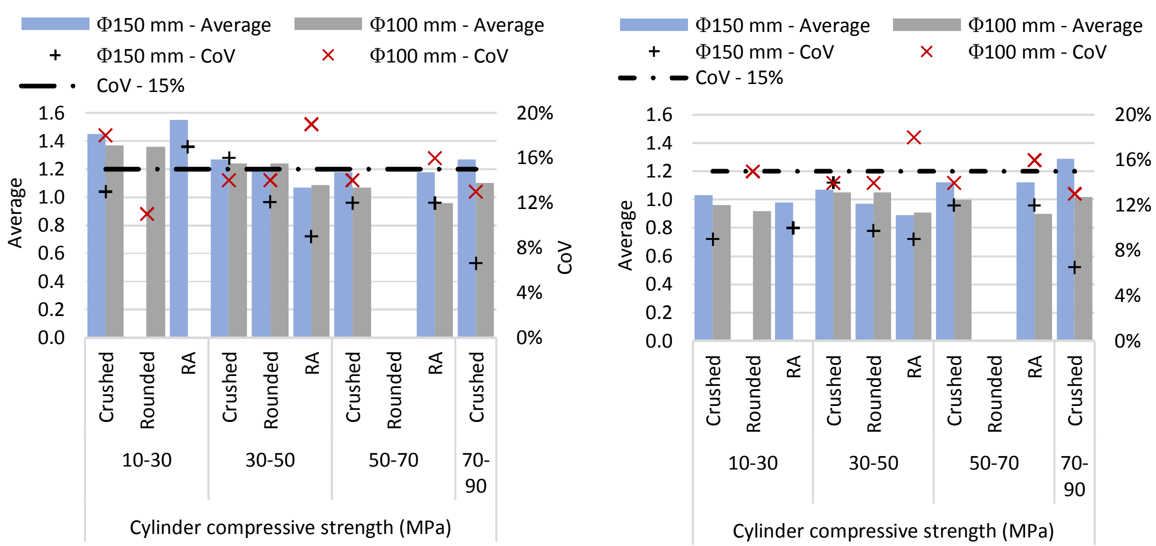


Fig. 11 Average and CoV of θ_{fct} for each population. Left: EC2 (2008); right: ACI 318.

Table 4 Average of the probability models.

	Average θ_{fct} for ϕ 150 mm		CoV	ϕ 100 / ϕ 150	
Aggregate morphology	Eurocode 2 (2008) and (2020); Model Code 2010	ACI 318	All codes	Eurocode 2 (2008) and (2020); Model Code 2010	ACI 318
CNA	1.25	1.15	15%	0.90	0.90
CRA	1.20	1.00	15%	0.85	0.90

Table 5 Estimated θ_{fctd}, $\theta_{ftk0.05}$, and $\theta_{ftk0.95}$.

	θ_{fctd}		$\theta_{fctk0.05}$		$\theta_{fctk0.95}$	
Aggregate morphology	CNA	CRA	CNA	CRA	CNA	CRA
Eurocode 2 (2008) and (2020), Model Code 2010	1.03	0.98	0.94	0.90	1.56	1.50
ACI 318	0.94	0.82	-	-	-	-

al. 2008);

5.3 Goodness-of-fit testing

As seen for θ_E, most distributions were suitably modelled by normal and lognormal distributions. Nevertheless, the use of these θ_{fct} is restricted to SLS reliability analyses since some datasets were ill-fitted in the lower tail region. If f_{ct} is a relevant parameter for ultimate limit states design, specific testing is recommended. Lognormal distributions fitted the data better than normal distributions in most instances (**Fig. 12**).

5.4 Proposed model for θ_{fct}

This section has a similar concept to section 4.4. Proposals are developed for CNA and CRA only, since data on RNA concrete are scarce and lack representativity. The conversion of the predicted to actual f_{ct} is analogue to the E_c conversion model:

$$f_{ct,actual} = \theta_{fct} \times f_{ct,code} \qquad (11)$$

θ_{fct} is normally distributed with a CoV of 15% and the expected values are shown in **Table 4**. Data were rounded to multiples of 0.05. The same weighing function of the θ_E proposition was used.

A CoV of 15% conservatively estimates the variability of most populations of the four codes (**Fig. 11**). The suitability of this CoV in an SLS reliability framework is assessed by comparing the design tensile strength (θ_{fctd} - calculated as shown in Equation (10) for θ_{Ed}) of the models proposed in **Table 4** with the θ_{fctd} of each dataset. The actual characteristic values of the 5% ($\theta_{fctk0.05}$) and 95% ($\theta_{fctk0.95}$) fractiles of f_{ct} were calculated for both Eurocode 2 versions and Model Code 2010. **Table 5** shows the θ_{fctd}, $f_{ctk0.05}$, and $f_{ctk0.95}$ obtained. Despite a better fit of lognormal distributions to the data (**Fig. 12**) normal distributions were used in the calculations due to convenience as well as conservationism in the lower tail region (Gulvanessian *et al*. 2002), since the skewness of the datasets was positive in almost all instances.

Figure 13 shows the relative errors (Δ_{rel}) between the θ_{fctd} calculated with the models of **Table 4** and those of each dataset. The Δ_{rel} of Eurocode 2 (2020) and Model Code 2010 relationships are analogue to those of Eurocode 2 (2008) (**Tables A.3** and **A.4** of the Appendix). The absolute errors (Δ_{abs}) are also shown in the Appendix.

The Δ_{rel} of ACI 318 was negligible for f_c below 70 MPa. A relative error of +20% was obtained for concrete in the 70 - 90 MPa strength range, which was considered acceptable (positive Δ_{rel} mean that the models proposed are conservative, and simplicity took precedence over developing a model with statistical descriptors that depended on f_c). The Δ_{rel} of both Eurocode 2

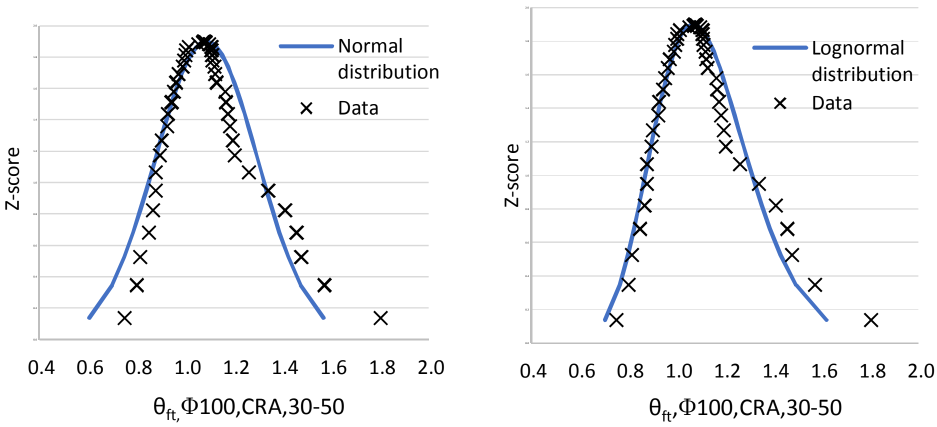
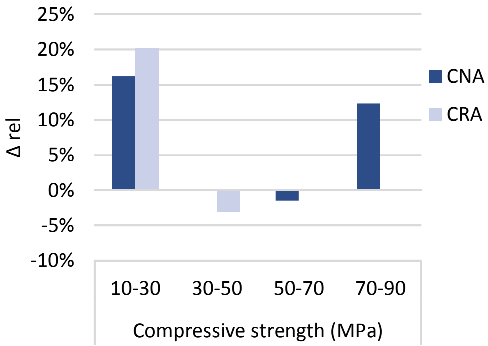


Fig. 12 θ_{fct} goodness-of-fit testing: left): normal distribution, right): lognormal distribution.



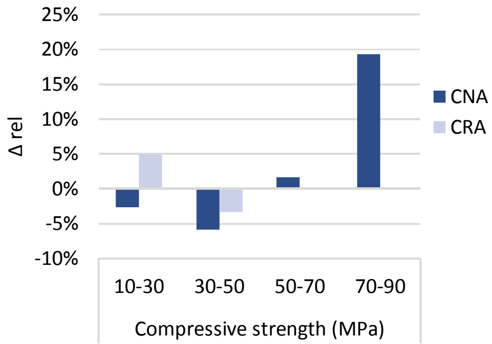


Fig. 13 Relative errors of θ_{fctd} when the proposed probability models are used. Left: Eurocode 2 (2008); right: ACI 318.

versions and Model Code 2010 was negligible for concrete of common strength ranges (30 to 70 MPa) and overly conservative for concrete with f_c between 10 - 30 MPa and 70 - 90 MPa. The reasoning for accepting the Δ_{rel} of ACI 318 also holds.

By definition, both Eurocode versions and Model Code 2010 predict $f_{ctk0.05}$ and $f_{ctk0.95}$ as 0.7 and 1.3 times the code estimative of f_{ct}. The data from Table 5 show that both predictions are below experimental data of the splitting tensile strength. A full-scope study on the relationship between the uniaxial tensile strength and the splitting tensile strength should follow, in order to assess whether codes are in fact underestimating $f_{ctk0.05}$ and $f_{ctk0.95}$. Underestimations of $f_{ctk0.95}$ are not conservative.

6. Conclusions

Current knowledge hinders reliability analyses on the serviceability limit-states of reinforced concrete structures, since the model uncertainties between code expectations and the actual tensile strength/Young's modulus have not been quantified probabilistically.

The importance of developing probabilistic models for these model uncertainties was discussed, as well as how the different mix designs and complex mechanisms of concrete behaviour hinder their assessment. Notwithstanding this fact, suitable models intended for SLS reliability assessment were developed for Eurocode 2, Model Code 2010 and ACI 318.

An extensive appraisal of 28-day test data coming from two specimens (ϕ 150 mm cylinders, the standard specimen of codes, and ϕ 100 mm cylinders) was made and the data were separated in different datasets to limit the influence of mix design on the evaluation of the model uncertainty.

Concerning the codified constitutive modelling of Young's modulus:

- The α factors of Eurocode 2 and Model Code 2010 do not reduce the aggregate's influence on the accuracy of code predictions;
- The model uncertainty was fairly dependent on the lithological type of coarse aggregate used in the mix design. This finding has a significant influence on the reliability of limit states related to concrete stiffness;
- Normal and lognormal distributions suit the modelling uncertainty sufficiently well for serviceability limit states;

A probabilistic model uncertainty factor was proposed for concrete produced with four different types of coarse natural aggregate and for concrete made with coarse recycled concrete aggregates.

- Concerning the code predictions of the tensile strength:

The model uncertainty was evaluated for concrete produced with coarse crushed natural aggregates and for concrete with coarse crushed recycled aggregates;

- The tensile strength of concrete with crushed natural aggregates is significantly underestimated by codes. ACI 318 predicted the splitting tensile strength better than the other documents but overestimates the tensile strength when recycled aggregates are used;
- The Eurocode predictions of the characteristic tensile strength seem considerable underestimations of the actual data;
- The model uncertainty of the Eurocode 2 and Model Code 2010 relationships depends on the compressive strength, which will affect the reliability of designs;

A probabilistic model uncertainty factor was proposed for crushed natural and crushed recycled aggregate concrete. If the compressive strength is higher than 70 MPa the splitting tensile strength should be tested;

- The tensile strength is commonly evaluated through splitting tests whilst Eurocode 2 and Model Code 2010 define the constitutive relationship in terms of the uniaxial tensile strength. If future probability models that convert splitting tensile strength data to uniaxial tensile strength are developed, they can be readily added to the model uncertainty proposed in this paper.

Notwithstanding the perceived notion that recycled concrete aggregates will result in concrete with uncertain behaviour, it was found that the scatter of the constitutive relationships of codes is similar to that of natural aggregates. Nevertheless, different model uncertainties should be used for different aggregate types (whether recycled or natural). Otherwise, reliability assessments are hindered by the unaccounted-for influence of the aggregates on the model uncertainty.

The tails of the probability distributions did not suitably represent the extreme values of the data. The models proposed in this paper should be used on reliability analyses on serviceability limit states only. Specific tests on Young's modulus and tensile strength are recommended whenever either of the properties is relevant for ultimate limit state design.

If constitutive relationships are analysed based on tests on ϕ 100 cylinders, Young's modulus and tensile strength predictions will be more conservative than if ϕ 150 cylinders are used. Conversion factors that reduce this effect were proposed.

Future research in this area should focus on the influence of aggregate types and morphologies on the actual reliability of concrete structures using the probability models proposed in this paper. The binder blends and strength ranges evaluated should be complemented by more experimental data. The model uncertainties of self-compacting concrete should also be assessed since they may differ from those studied in this paper.

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Notation

Abbreviations

BS - basalt
CAN - crushed natural aggregates
CoV - coefficient of variation
CRA - crushed recycled aggregates
FA - fly ash
GGBS - ground granulated blast-furnace slag
GR - granite
ITZ - interfacial transition zone
LS - Limestone
OPC - ordinary Portland cement
QZ - quartzite
RA - recycled concrete aggregates
RNA - rounded natural aggregates
SF - silica fume
SLS - serviceability limit-state
SS - sandstone

Symbols

E_c - Young's modulus of concrete
E_{cm} - average E_c
f_c - compressive strength of concrete
f_{ck} - characteristic f_c
f_{cm} - average f_c
f_{ct} - tensile strength of concrete
f_{ctm} - average f_{ct}
$f_{ctm,splt}$ - average splitting tensile strength

α - Eurocode/Model Code aggregate correction factor

$\alpha_{R,FORM}$ - sensitivity factor of a leading resistance variable (EN 1990)

Δ_{abs} - absolute errors of the proposed models in comparison to the data

Δ_{rel} - relative errors of the proposed models in comparison to the data

θ_E - model uncertainty of f_c vs. E_c constitutive relationship

θ_{Ed} - estimate of the design value of θ_E

θ_{fct} - model uncertainty of f_c vs. f_{ct} constitutive relationship

θ_{fctd} - estimate of the design value of θ_{fct}

$\theta_{fctk\,0.05}$ - 5% fractile of θ_{fct}

$\theta_{fctk\,0.95}$ - 95% fractile of θ_{fct}

Appendix

Table A. 1 fc vs. Ec: Statistics of the ϕ 150 mm cylinders. More than 7 mixes only.

	Limestone															
	f_c: 10-30 MPa				f_c: 30-50 MPa				f_c: 50-70 MPa				f_c: 70-90 MPa			
	θEC2_2008	θMC10	θEC2_2020	θACI318	θEC2_2008	θMC10	θEC2_2020	θACI318	θEC2_2008	θMC10	θEC2_2020	θACI318	θEC2_2008	θMC10	θEC2_2020	θACI318
Count	13				50				22				12			
% most	31%				26%				45%				67%			
Average	1.20	1.19	1.19	1.33	1.19	1.16	1.16	1.21	1.23	1.19	1.18	1.15	1.23	1.18	1.17	1.08
CoV	11%	11%	11%	11%	14%	14%	14%	14%	13%	13%	13%	12%	8%	8%	8%	8%
θ_{Ed}	106%	105%	105%	117%	101%	99%	99%	103%	107%	103%	103%	100%	113%	108%	108%	99%
Δ abs	1%	5%	4%	17%	-4%	-1%	-2%	2%	2%	2%	2%	-1%	8%	8%	7%	-1%
Δ rel	1%	4%	4%	14%	-4%	-1%	-2%	2%	2%	2%	2%	-1%	7%	7%	7%	-1%
	Quartzite															
	f_c: 10-30 MPa				f_c: 30-50 MPa				f_c: 50-70 MPa				f_c: 70-90 MPa			
	θEC2_2008	θMC10	θEC2_2020	θACI318	θEC2_2008	θMC10	θEC2_2020	θACI318	θEC2_2008	θMC10	θEC2_2020	θACI318	θEC2_2008	θMC10	θEC2_2020	θACI318
Count	14				49				14				11			
% most	64%				53%				79%				100%			
Average	0.92	0.91	0.91	1.15	0.98	0.96	0.96	1.12	1.01	0.98	0.98	1.06	1.02	0.98	0.98	1.01
CoV	8%	8%	8%	9%	7%	7%	7%	7%	11%	11%	11%	11%	2%	2%	2%	3%
θEd	0.84	0.83	0.83	1.04	0.91	0.89	0.89	1.03	0.90	0.86	0.86	0.93	1.00	0.95	0.95	0.97
Δ abs	-0.04	0.00	0.00	0.12	0.03	0.06	0.06	0.11	0.02	0.03	0.03	0.01	0.13	0.12	0.12	0.06
Δ rel	-5%	0%	0%	12%	4%	7%	6%	11%	2%	4%	4%	1%	13%	13%	13%	6%
	Basalt															
	f_c: 30-50 MPa				f_c: 50-70 MPa				f_c: 70-90 MPa				f_c: 90-110 MPa			
	θEC2_2008	θMC10	θEC2_2020	θACI318	θEC2_2008	θMC10	θEC2_2020	θACI318	θEC2_2008	θMC10	θEC2_2020	θACI318	θEC2_2008	θMC10	θEC2_2020	θACI318
Count	23				50				28				16			
% most	70%				90%				79%				44%			
Average	0.89	0.87	0.86	1.18	0.89	0.87	0.86	1.18	0.89	0.87	0.86	1.18	0.89	0.87	0.86	1.18
CoV	12%	12%	12%	11%	12%	12%	12%	11%	12%	12%	12%	11%	12%	12%	12%	11%
θEd	0.78	0.76	0.76	1.04	0.78	0.76	0.76	1.04	0.78	0.76	0.76	1.04	0.78	0.76	0.76	1.04
Δ abs	-0.01	-0.03	-0.03	0.08	-0.01	-0.03	-0.03	0.08	-0.01	-0.03	-0.03	0.08	-0.01	-0.03	-0.03	0.08
Δ rel	-1%	-4%	-4%	8%	-1%	-4%	-4%	8%	-1%	-4%	-4%	8%	-1%	-4%	-4%	8%
	Granite															
	f_c: 30-50 MPa				f_c: 50-70 MPa				f_c: 70-90 MPa				f_c: 90-110 MPa			
	θEC2_2008	θMC10	θEC2_2020	θACI318	θEC2_2008	θMC10	θEC2_2020	θACI318	θEC2_2008	θMC10	θEC2_2020	θACI318	θEC2_2008	θMC10	θEC2_2020	θACI318
Count	44				55				52				17			
% most	43%				80%				67%				88%			
Average	0.87	0.85	0.85	0.97	0.79	0.76	0.76	0.82	0.85	0.82	0.81	0.83	0.99	0.94	0.93	0.92
CoV	14%	14%	14%	14%	11%	11%	11%	12%	12%	12%	12%	12%	7%	7%	7%	7%
θEd	0.74	0.72	0.72	0.83	0.69	0.67	0.67	0.72	0.75	0.72	0.71	0.73	0.91	0.87	0.86	0.86
Δ abs	0.00	0.03	0.02	0.09	-0.05	-0.03	-0.03	-0.03	0.01	0.02	0.01	-0.01	0.17	0.17	0.16	0.11
Δ rel	0%	3%	3%	10%	-7%	-5%	-5%	-4%	1%	2%	2%	-1%	19%	19%	19%	13%
	Recycled concrete aggregate															
	f_c: 10-30 MPa				f_c: 30-50 MPa				f_c: 50-70 MPa				f_c: 70-90 MPa			
	θEC2_2008	θMC10	θEC2_2020	θACI318	θEC2_2008	θMC10	θEC2_2020	θACI318	θEC2_2008	θMC10	θEC2_2020	θACI318	θEC2_2008	θMC10	θEC2_2020	θACI318
Count	16				35				18				7			
% most	38%				20%				50%				71%			
Average	1.31	1.31	1.30	1.16	1.22	1.19	1.19	0.97	1.33	1.28	1.28	0.97	1.21	1.15	1.15	0.82
CoV	13%	13%	13%	15%	11%	11%	11%	11%	12%	12%	12%	13%	7%	7%	7%	7%
θEd	1.14	1.13	1.13	0.97	1.08	1.06	1.06	0.86	1.16	1.12	1.12	0.84	1.12	1.07	1.07	0.76
Δ abs	0.09	0.08	0.08	0.19	0.03	0.01	0.01	0.07	0.11	0.07	0.07	0.06	0.07	0.02	0.02	-0.03
Δ rel	8%	7%	7%	19%	3%	1%	1%	8%	10%	6%	6%	7%	7%	2%	2%	-4%

Note: "% most" is the maximum percentage of mixes coming from a single paper

Table A. 2: f_c vs. E_c: Statistics of the ϕ 100 mm cylinders. More than 7 mixes only.

	Limestone															
	f_c: 10-30 MPa				f_c: 30-50 MPa				f_c: 50-70 MPa				f_c: 70-90 MPa			
	θEC2_2008	θMC10	θEC2_2020	θACI318	θEC2_2008	θMC10	θEC2_2020	θACI318	θEC2_2008	θMC10	θEC2_2020	θACI318	θEC2_2008	θMC10	θEC2_2020	θACI318
Count	10				48				42				25			
% most	40%				44%*				57%*				36%			
Average	1.01	1.01	1.00	1.13	1.04	1.01	1.01	1.05	1.13	1.09	1.08	1.05	1.15	1.10	1.10	1.01
STdev	0.16	0.15	0.15	0.18	0.13	0.13	0.13	0.14	0.13	0.13	0.12	0.12	0.15	0.14	0.14	0.13
CoV	15%	15%	15%	16%	13%	13%	13%	13%	12%	12%	12%	11%	13%	13%	13%	12%
	Sandstone															
	f_c: 10-30 MPa				f_c: 30-50 MPa				f_c: 50-70 MPa				f_c: 70-90 MPa			
	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}
Count					16				13				11			
% most					56%				62%				100%			
Average					1.17	1.15	1.15	0.94	1.08	1.04	1.03	0.77	1.04	0.99	0.99	0.68
STdev					0.10	0.10	0.10	0.08	0.08	0.08	0.08	0.06	0.04	0.04	0.04	0.03
CoV					9%	8%	8%	8%	8%	8%	8%	8%	4%	4%	4%	4%
	Basalt															
	f_c: 10-30 MPa				f_c: 30-50 MPa				f_c: 50-70 MPa				f_c: 70-90 MPa			
	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}
Count					13											
% most					46%											
Average					0.82	0.80	0.80	1.11								
STdev					0.17	0.16	0.16	0.22								
CoV					21%	20%	20%	20%								
	Granite															
	f_c: 10-30 MPa				f_c: 30-50 MPa				f_c: 50-70 MPa				f_c: 70-90 MPa			
	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}
Count					25				20				8			
% most					60%				40%				63%			
Average					0.90	0.88	0.88	1.01	0.95	0.91	0.91	0.99	0.91	0.87	0.87	0.90
STdev					0.10	0.10	0.10	0.13	0.07	0.07	0.07	0.07	0.14	0.14	0.14	0.15
CoV					11%	11%	11%	12%	8%	8%	8%	7%	16%	16%	16%	16%
	Recycled concrete aggregate															
	f_c: 10-30 MPa				f_c: 30-50 MPa				f_c: 50-70 MPa				f_c: 70-90 MPa			
	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}
Count	14				29				10							
% most	36%				28%				46%							
Average	1.23	1.22	1.21	1.07	1.15	1.12	1.12	0.91	1.14	1.10	1.10	0.83				
STdev	0.18	0.19	0.19	0.23	0.11	0.10	0.10	0.09	0.05	0.05	0.05	0.04				
CoV	14%	15%	15%	21%	9%	9%	9%	10%	5%	5%	5%	5%				

Table A. 3: f_c vs. f_{ct}: Statistics of the ϕ 100 mm cylinders. More than 7 mixes only.

	Crushed natural aggregates															
	f_c: 10-30 MPa				f_c: 30-50 MPa				f_c: 50-70 MPa				f_c: 70-90 MPa			
	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}
Count	15				86				30				12			
% most	20%				27%				23%				33%			
Average	1.45	1.45	1.45	1.03	1.27	1.27	1.27	1.07	1.18	1.18	1.18	1.12	1.27	1.29	1.29	1.29
STdev	0.19	0.19	0.19	0.10	0.20	0.20	0.20	0.15	0.14	0.14	0.15	0.14	0.08	0.08	0.08	0.08
CoV	13%	13%	13%	9%	16%	16%	16%	14%	12%	12%	12%	12%	7%	7%	7%	7%
Skew	1.33	1.33	1.33	0.01	0.41	0.41	0.41	0.20	0.41	0.41	0.38	0.42	-0.37	-0.39	-0.39	-0.39
Kurt	1.78	1.78	1.78	0.33	0.43	0.43	0.43	0.53	1.00	1.00	0.92	1.18	0.90	1.21	1.21	1.21
θEd	1.22	1.22	1.22	0.92	1.03	1.03	1.03	0.89	1.01	1.01	1.01	0.96	1.17	1.19	1.19	1.19
Δ abs	0.20	0.20	0.20	-0.02	0.00	0.00	0.00	-0.05	-0.01	-0.01	-0.01	0.02	0.14	0.16	0.16	0.25
Δ rel	16%	16%	16%	-3%	0%	0%	0%	-6%	-1%	-1%	-1%	2%	12%	14%	14%	21%
	Rounded natural aggregates															
	f_c: 10-30 MPa				f_c: 30-50 MPa											
	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}
Count					13											
% most					46%											
Average					1.19	1.19	1.19	0.97								
STdev					0.14	0.14	0.14	0.09								
CoV					12%	12%	12%	10%								
Skew					0.15	0.15	0.15	0.23								
Kurt					-0.24	-0.24	-0.24	-0.8								
	Crushed recycled concrete aggregates															
	f_c: 10-30 MPa				f_c: 30-50 MPa				f_c: 50-70 MPa				70-90			
	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}
Count	9				24				17							
% most	52%				29%				53%							
Average	1.55	1.55	1.55	0.98	1.07	1.07	1.07	0.89	1.18	1.18	1.18	1.12				
STdev	0.26	0.26	0.26	0.10	0.10	0.10	0.10	0.08	0.14	0.14	0.15	0.14				
CoV	17%	17%	17%	10%	9%	9%	9%	9%	12%	12%	12%	12%				
Skew	0.28	0.28	0.28	1.05	0.34	0.34	0.34	0.41	0.41	0.41	0.38	0.42				
Kurt	-0.74	-0.74	-0.74	0.21	-1.25	-1.25	-1.25	0.04	1.00	1.00	0.92	1.18				
θEd	1.23	1.23	1.23	0.86	0.95	0.95	0.95	0.79	1.01	1.01	1.01	0.96				
Δ abs	0.25	0.25	0.25	0.04	-0.03	-0.03	-0.03	-0.03	0.03	0.03	0.03	0.14				
Δ rel	20%	20%	20%	5%	-3%	-3%	-3%	-3%	3%	3%	3%	14%				

Table A.4: f_c vs. f_{ct}: Statistics of the ϕ 100 mm cylinders. More than 7 mixes only.

	Crushed natural aggregates															
	f_c: 10-30 MPa				f_c: 30-50 MPa				f_c: 50-70 MPa				f_c: 70-90 MPa			
	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}
Count	34				125				44				36			
	21%				14%				18%				21%			
Average	1.37	1.37	1.37	0.96	1.24	1.24	1.24	1.05	1.07	1.07	1.07	1.00	1.10	1.10	1.12	1.02
STdev	0.24	0.24	0.24	0.20	0.18	0.18	0.18	0.14	0.15	0.15	0.15	0.14	0.14	0.14	0.15	0.13
CoV	0.18	0.18	0.18	0.21	14%	14%	14%	14%	14%	14%	14%	14%	13%	13%	13%	13%
Skew	-0.34	-0.34	-0.34	-0.44	0.66	0.66	0.66	0.57	0.46	0.46	0.46	0.39	0.20	0.20	0.25	0.07
Kurt	0.20	0.20	0.20	0.76	0.90	0.90	0.90	0.53	0.92	0.92	0.94	0.91	1.96	1.96	1.96	1.96
	Rounded natural aggregates															
	f_c: 10-30 MPa				f_c: 30-50 MPa											
	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}								
Count	14				17											
	86%				71%											
Average	1.36	1.36	1.36	0.92	1.24	1.24	1.24	1.05								
STdev	0.14	0.14	0.14	0.14	0.18	0.18	0.18	0.14								
CoV	11%	11%	11%	15%	14%	14%	14%	14%								
Skew	1.33	1.33	1.33	1.40	0.66	0.66	0.66	0.57								
Kurt	2.49	2.49	2.49	3.19	0.90	0.90	0.90	0.53								
	Crushed recycled concrete aggregates															
	f_c: 10-30 MPa				f_c: 30-50 MPa				f_c: 50-70 MPa							
	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}	$\theta_{EC2,2008}$	θ_{MC10}	$\theta_{EC2,2020}$	θ_{ACI318}				
Count					46				18							
					33%				61%							
Average					1.09	1.09	1.09	0.91	0.96	0.96	0.96	0.90				
STdev					0.21	0.21	0.21	0.17	0.15	0.15	0.15	0.14				
CoV					19%	19%	19%	18%	16%	16%	16%	16%				
Skew					1.20	1.20	1.20	0.68	1.61	1.61	1.62	1.67				
Kurt					2.21	2.21	2.21	0.73	2.55	2.55	2.58	2.95				