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Effect of specimen geometry and specimen preparation on the concrete compressive strength test

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Abstract. This paper discusses an experimental programme that was carried out to study the effects of specimen size-shape and type of moulds on the compressive strength of concrete. For this purpose, cube specimens with 150 mm dimensions, cylinder specimens with 150×300 mm dimensions, and prism specimens with 150×150×375 mm dimensions were prepared. The experimental programme was carried out with several concrete compositions belonging to strength classes C20/25, C25/30, C30/37, C40/50 and C60/75. Furthermore, the test results were curve-fitted using the least squares method to obtain the new parameters for the modified size effect law.

Keywords: compressive strength; size effect; specimen geometry; cure conditions

1. Introduction

The applicable code of practice provisions to determine the concrete compressive strength permits different geometric dimensions for specimens. However, the compressive strength of concrete is pointedly affected by the size and aspect ratio of specimens due to aggregates, altered frictions between concrete surfaces and loading platen, and differences of crack propagation and localized failure zone (Bazant and Planas 1998). It has been mostly identified that the concrete compressive strength reduces with the increase of the section size of the specimen, however the reducing rate almost remains constant beyond a certain size limit (Sarıdemir 2014, Chin *et al.* 1997, Alejandre *et al.* 2014). Also, the compressive strength measured from a cube is usually greater than that detailed from a cylinder, while the effect of the section shape of the specimen on the size effect is slightly disputed (Wu *et al*. 2015, Yi *et al.* 2006, Aslani 2013, Tung *et al.* 2015, Sim *et al.* 2013).

Sizes and shapes of test specimens to define the compressive strength of the concrete are diverse for most countries. But, frequently used specimens are cylinders and cubes. Cylinders with diameter 150 mm and height 300 mm (henceforth '150×300 mm cylinder') are used in the United States, South Korea, France, Canada, Australia, and other countries while cubes with edge 150 mm (henceforth '150 mm cube') are the standard specimens used in the United Kingdom, Germany, and several other European countries.

Hence, the codes of practice accurately reference the ratio of 150×300 mm cylinder strength to 150 mm cube strength and they state a correction factor for concrete strengths to recompense for the decreased strength when the aspect ratio of specimen is less than 2.0 (ASTM Standards 2001, CEB-FIP 1999, Eurocode 4 2004). However, the provisions do not specially explain the applicability and/or adjustment of the correction factors for the effect of specimen geometry and specimen preparation on the concrete compressive strength results. Besides, studies were mostly developed using concrete produced with granitic or limestone aggregates. Bearing in mind that the size and shape effects on concrete compressive strength are influenced by the structure and void between pastes and aggregate particles with the spread of a number of cracks in the local failure zone (Bazant 1984, Bazant and Xiang 1997), in this research concrete was produced with aggregates from volcanic products. As far as the authors know, there is not any study that investigated the size and shape effects on concrete compressive strength using aggregates from volcanic products.

This study assessed the accuracy of the ratio used in Eurocode 2 (2004) between the compressive strength measured by cubic, cylindrical, and prism specimens. This study was carried out with several commercial concrete compositions belonging to strength classes C20/25, C25/30, C30/37 and C40/50. For each concrete composition the compressive strength test with cubic, cylindrical, and prism specimens measured at 28 days were evaluated. This study aims to contribute to the clarification of the test results of the concrete compressive strength. In this work we intend to know:

(a) What is the influence of the geometric shape of the specimen in the test result of compressive strength,

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namely the differences for tests carried out in cubic vs. cylindrical specimens, cubic vs. prismatic specimens, and cylindrical vs. prismatic specimens?

(b) If the material in which the moulds are fabricated, namely cast iron and polyurethane, affects the value measured in the compressive strength test? And do we need smooth compressions surfaces of the specimens moulded in cast iron moulds?

(c) How the compressive strength test value is affected when specimens are removed from controlled humidity and temperature long time before testing (for instance 2 hours)?

(d) If the specimens are subjected to E-modulus test prior to compressive strength test, the compressive strength value is affected?

Finally, in this study also mathematically derived a basic formula, following the concept of the crack band theory (Bazant 1984, Bazant and Xiang 1997, Kim and Eo 1990) of fracture mechanics in order to recognize the effects of the aspect ratio of the specimen and the concrete unit weight on the size effect. The unknown coefficients in the proposed basic formula were determined by the least square method using a comprehensive database.

2. Experimental programme

2.1 Concrete mixtures

In order to complete the goal of this experimental study, eight sets of specimens were collected from eight distinct mixtures of commercial concrete belonging to strength classes C20/25, C25/30, C30/37, C40/50 and C60/75. Seven mixtures correspond to commercial conventional concretes produced in two different concrete plants in the Madeira Island (Portugal). Three mixtures were from the concrete Plant *X* and four from the concrete Plant *Y*. The eighth mixture was a self-compacting concrete supplied by another concrete producer (Plant *Z*).

All concrete mixtures were made with materials currently available in the Madeira Island market. All mixtures were produced with Cement CEM II/A-L 42.5R (EN 197-1 2011) and with aggregates from volcanic origin (mostly, mineral olivine, pyroxene and plagioclase) produced in accordance with EN 12620 (2013) with relative to alkali-silica reactions are classified as Class I - unreactive added (Silva 2012). Although each concrete plant used aggregates coming from its own stone-quarry (i.e., there were three different sources of aggregates), all concrete producers used two crushed gravels and two sands to produce their concretes, all the size of the grains being classified into crushed gravel 1 (4/12), crushed gravel 2 (12/20) with a maximum size of 22 mm, coarse sand (2/6), and fine sand (0/4).

Table 1 presents the information provided by producers for each mixture, namely constituent materials proportions, commercial compressive strength class and the consistency measured by the slump test (EN 12350-8, 2010). Regarding to the SCC mixture, it was composed by 134 (kg/m^3) of fly ash - as the binder comprises 70% cement and 30% fly ash by volume, meaning a water/binder 0.31. The fresh properties tests for SCC were performed all in accordance with EN 12350-8, 9, 10 and 11 (EN 12350-8 2010, EN 12350-9 2010, EN 12350-10 2010, EN 12350-11 2010) being found the slump-flow class SF3, the viscosity class VF1, the passing ability PL2 and segregation resistance class SR2 (Aslani and Nejadi 2012a, b, c, d, e, Aslani and Nejadi 2013a, b, Aslani 2013, Aslani and Maia 2013, Aslani and Natoori 2013, Aslani 2014, Aslani and Bastami 2014, Aslani *et al*. 2014a, b, 2015, Maia and Aslani 2016, Jalal 2014, Li and An 2014, Mastali *et al*. 2016, Zarrin and Khoshnoud 2016, Nazarpour and Foroughi Asl 2016).

2.2 Specimens

The following specimens were collected for each mixture: (i) ten cubic specimens with 150 mm of edge cast in a cubic moulds fabricated with cast iron; (ii) ten cubic specimens with 150 mm of edge cast in a cubic moulds fabricated with polyurethane; (iii) six cylindrical specimens with 150 mm of diameter and 300 mm of height cast in a cubic moulds fabricated with polyurethane; and (iv) two prismatic specimens with square base with 150 mm of edge and 750 mm of length cast in a cubic moulds fabricated with cast iron (each one of this prismatic specimen is, later, cut in two pieces with 370 mm length). All the moulds belonging to the LREC (Regional Civil Engineering Laboratory), all calibrated, waterproof and non-absorbent were used.

Casting and curing of the specimens were carried out in accordance with EN 12390-2 (2009). Each mould was filled into two layers and compacted by mechanical vibration with a needle vibrator. The concrete was compacted after placing in the mould in order to obtain full compaction without segregation. According to EN 12390-2 (2009), the specimen in the mould may leave between 16 and 72 hours, protected from shock, excessive vibration and dehydration at 20±5℃. Specimens X-1 were within the mould until the age of 48 hours as the remaining specimens were within the mould until the age of 24 hours.

Cubic polyurethane moulds were removed by compressed air introduced at the base. The remaining moulds were removed after disassembly using appropriate tools for bolts. After moulds removed, the specimens were placed in water at a temperature of 20±2℃ in the LREC installations. The preparation of the specimens (cut and smooth surfaces) was performed 5±1 days before tests. During its preparation, all specimens were out of water less than 60 minutes. Seeing that the prismatic specimens cast had length of 750 mm, they were cut into two specimens with 370 mm in length.

Just before each compressive strength test, the corresponding specimen was removed from the water and with slightly damp towel excess water and any extra material from the surfaces of the specimens were removed. Then, the size and mass of all specimens were measured and parallelism between surfaces and surface irregularities were checked - either the measurements or parallelism and surface irregularities satisfied the EN 12390-1 (2012) requirements. Subsequently, the compressive strength test

Table 1 The proportions of the concrete mixes

Mix	Cement [kg/m^3]	Fine sand [kg/m^3]	Coarse sand [kg/m^3]	Fine gravel [kg/m^3]	Coarse gravel [kg/m^3]
X-1	305	640	368	541	413
X-2	355	571	624	716	0
X-3	375	571	624	716	0
Y-1	244	1179	0	386	575
Y-2	255	1195	0	399	581
Y-3	297	1204	0	421	608
Y-4	402	977	66	392	584
Z-1	412	609	397	475	203

Mix	Water [kg/m^3]	Admixture [kg/m^3]	w/c	D_{max} [mm]	Commercial strength class	Slump [mm]
X-1	210	3.65	0.69	22	C20/25	130
X-2	225	4.26	0.63	11	C25/30	140
X-3	225	4.47	0.6	11	C30/37	130
Y-1	154	3.00	0.71	20	C20/25	160
Y-2	138	4.32	0.6	20	C25/30	140
Y-3	119	4.98	0.48	20	C30/37	120
Y-4	151	6.63	0.4	20	C40/50	140
Z-1	53	4.84	0.41	16	C60/75	–

was carried out (except for specimens that had to rest 120 minutes at environmental conditions and for the ones wherein the E-modulus test were carried out-see subsection 2.3).

2.3 Compressive strength tests

The concrete compressive strength tests have been done based on the EN 12390-4 (2003). The procedure of this test in EN 12390-4 (2003) is summarized in the preparation and positioning of test specimens, load application, assessment of the type of rupture and presenting the results. Note that in cylindrical specimens loading was applied at the rate of 10.6 kN/s and in cubic and prismatic specimens loading was applied at the rate of 13.5 kN/s. The experimental programme for each mixture was organized on the following sets:

(a) Five cubic specimens moulded in polyurethane moulds (CP) wherein the compressive strength tests were carried out almost immediately after removing specimens from water;
(b) Five cubic specimens moulded with polyurethane moulds wherein specimens had to rest for 120 minutes (CP120) at the environment conditions after being removed from the water up to the compressive strength tests were carried out;
(c) Five cubic specimens moulded with cast iron moulds (CI) wherein the compressive strength tests were carried out almost immediately after removing specimens from water;
(d) Five cubic specimens similar to CI specimens but wherein the compression surfaces of these test specimens were previously (5±1 days before) smoothed (CIS);
(e) Four prismatic test specimens (PR) with a square base of 150 mm and 370 mm edge length wherein the compressive strength tests were carried out almost immediately after removing specimens from water;
(f) Three cylindrical specimens moulded with polyurethane moulds (CY) wherein the compressive strength tests were carried out almost immediately after removing specimens from water;
(g) Three cylindrical specimens moulded with polyurethane moulds (CYEM) wherein the E-modulus test was carried out before the compressive strength test.

3. Experimental results

According to EN 12390-3 (2009), the compressive strength is calculated from Eq. (1), where f_c is the compressive strength (MPa), F is the maximum load at break (N) and A_c is the area cross section (mm^2) of the specimen in which the compression force has been applied.

$$f_c = \frac{F}{A_c} \tag{1}$$

After the calculation of compressive strength for each specimen, the average value and standard deviation of the set was calculated. Table 2 reports those values.

4. Analysis and discussion of the compressive strength values measured

The analysis of the values of the compressive strength measured in the experimental programme is done in several parts. First the comparison of results measured in cubic specimens (no geometry changes) is analysed: (i) the influence of the material in which moulds are fabricated, (ii) the effect of previously smoothing the compression faces, and (iii) the effect of the specimen resting time (120 minutes) at the environment conditions before the compressive strength test. Afterwards the comparison of results measured in specimens with different geometry is analysed: (iv) the relationship between cubic and cylindrical specimens, (v) the relationship between cubic and prismatic specimens, and (vi) the relationship between cylindrical and prismatic specimens are checked. Finally, it is checked (vii) the effect of carrying out the E-modulus test before to execute the compressive strength test on the same specimen.

4.1 Results of cubic specimens for cast iron moulds versus polyurethane moulds

Analysing the values of Table 2 for cubic specimens cast in moulds fabricated with cast iron ('CI') and the ones cast in moulds fabricated with polyurethane ('CP') one observes that compressive strength results of cubic specimens moulded in cast iron moulds ('CI') are frequently higher than the ones of polyurethane moulds ('CP'). Table 3 summarizes that increase (percentage) of the compressive

Table 2 Compressive strength results

Mix	Commercial Strength Class	Specimen	Were surfaces mechanically smoothed?	Surface conditions	Number of specimens tested	Average value and standard deviation of the compressive strength (f_c) measure [MPa]
X-1	C20/25	CP	No	Wet	5	24.6 ± 0.43
		CP120	No	Dry	5	25.5 ± 0.54
		CI	No	Wet	5	26.9 ± 0.27
		CIS	Yes	Wet	5	27.4 ± 0.52
		CY	Yes	Wet	3	24.0 ± 0.22
		CYEM	Yes	Wet	3	24.2 ± 0.30
		PR	Yes	Wet	4	22.1 ± 0.41
X-2	C25/30	CP	No	Wet	5	36.9 ± 1.37
		CP120	No	Dry	5	38.6 ± 0.54
		CI	No	Wet	5	40.8 ± 0.24
		CIS	Yes	Wet	5	41.0 ± 0.50
		CY	Yes	Wet	3	36.6 ± 0.50
		CYEM	Yes	Wet	3	36.6 ± 0.15
		PR	Yes	Wet	4	31.2 ± 3.78
X-3	C30/37	CP	No	Wet	5	45.6 ± 1.10
		CP120	No	Dry	5	44.9 ± 0.81
		CI	No	Wet	5	47.3 ± 0.49
		CIS	Yes	Wet	5	48.1 ± 0.73
		CY	Yes	Wet	3	43.7 ± 0.68
		CYEM	Yes	Wet	3	44.2 ± 0.43
		PR	Yes	Wet	4	42.6 ± 2.06
Y-1	C20/25	CP	No	Wet	5	30.4 ± 0.78
		CP120	No	Dry	5	30.4 ± 0.29
		CI	No	Wet	5	31.2 ± 0.58
		CIS	Yes	Wet	5	31.5 ± 0.51
		CY	Yes	Wet	3	27.5 ± 0.21
		CYEM	Yes	Wet	3	27.5 ± 0.35
		PR	Yes	Wet	4	27.2 ± 0.29
Y-2	C25/30	CP	No	Wet	5	38.1 ± 2.31
		CP120	No	Dry	5	39.3 ± 1.00
		CI	No	Wet	5	40.2 ± 2.19
		CIS	Yes	Wet	5	41.2 ± 1.36
		CY	Yes	Wet	3	37.5 ± 0.60
		CYEM	Yes	Wet	3	37.4 ± 0.38
		PR	Yes	Wet	4	33.6 ± 1.33
Y-3	C30/37	CP	No	Wet	5	41.1 ± 0.64
		CP120	No	Dry	5	41.3 ± 1.41
		CI	No	Wet	5	42.0 ± 0.41
		CIS	Yes	Wet	5	43.2 ±0.61
		CY	Yes	Wet	3	38.8 ± 0.14
		CYEM	Yes	Wet	3	38.6 ± 0.26
		PR	Yes	Wet	4	34.9 ± 2.09
Y-4	C40/50	CP	No	Wet	5	64.4 ± 2.17
		CP120	No	Dry	5	62.3 ± 2.51
		CI	No	Wet	5	67.2 ± 0.82
		CIS	Yes	Wet	5	69.1 ± 0.79
		CY	Yes	Wet	3	62.4 ± 1.20
		CYEM	Yes	Wet	3	63.2 ± 0.43
		PR	Yes	Wet	4	56.7 ± 1.17
Z- 1	C60/75	CP	No	Wet	5	73.2 ± 2.50
		CP120	No	Dry	5	73.1 ± 5.60
		CI	No	Wet	5	80.5 ± 4.55
		CIS	Yes	Wet	5	78.5 ± 3.53
		CY	Yes	Wet	3	71.2 ± 0.70
		CYEM	Yes	Wet	3	71.3 ± 1.82
		PR	Yes	Wet	4	66.4 ± 0.77

Table 3 Increase percentage in compressive strength of 'CP' to 'CI' specimens

Mix	Class	CI/CP-100%
X-1	C20/25	9.35%
X-2	C25/30	10.57%
X-3	C30/37	3.73%
Y-1	C20/25	2.63%
Y-2	C25/30	5.51%
Y-3	C30/37	2.19%
Y-4	C40/50	4.35%
Z-1	C60/75	9.97%
Average	-	6.04%

strength with the X-1, X-2, and Z-1 mixes results being about 10% higher and for the other mixes the increase ranged from 2.2 to 5.5%.

Thus, it is concluded that the material in which the mould is fabricated influences the value measured of the compressive strength. Bearing in mind that in this study we are comparing moulds fabricated with polyurethane and cast iron, possibly the difference found is due to lower temperature developed during early ages. As the polyurethane has lower thermal conductivity than the cast iron, probably these specimens reached high temperature up to the demoulding time. Then, these specimens should present higher concrete strength at early ages (at the demoulding time) however lower concrete strength at mature ages than the ones cast in cast iron moulds. This hypothesis could be checked by measuring the concrete strength at the demoulding time, nevertheless such tests were not carried out during this experimental programme.

4.2 Results of cubic specimens for cast iron moulds versus specimens for cast iron moulds with compression surfaces being smoothed for the compressive strength test

It is not necessary to smooth compression surfaces typically in cubic specimens. In fact this is one of the biggest advantages of using cubic specimens. However, sometimes, in this concern doubts are raised when moulds need to by assembled (habitually, metallic moulds), are worn-out (high dispersion values are observed) or when comparison have to be done with other specimens with compression surfaces smoothed. Bearing in mind that authors would want to compare results between cubic and prismatic and cylindrical specimens (the prismatic and cylindrical specimens with smoothed compression surfaces) and that cast iron moulds were assembled, check the effect of smoothing compression surfaces becomes important. In Table 4 the comparison between the compressive strength measured in specimens cast in cast iron moulds with and without smoothing the compression surfaces is evaluated.

Considering values reported in Table 4, one concludes that smoothing the compression surfaces of specimens cast in cast iron moulds leads to a slight increase of the concrete compressive strength. In fact, only for the SCC (Z-1) mixture the compressive strength value decreased with

Table 4 Comparison of the compressive strength between specimens with and without smoothed compressions surfaces

Mix	Class	CIS/CI-100%
X-1	C20/25	1.86%
X-2	C25/30	0.49%
X-3	C30/37	1.69%
Y-1	C20/25	0.96%
Y-2	C25/30	2.49%
Y-3	C30/37	2.86%
Y-4	C40/50	2.83%
Z-1	C60/75	-2.48%
Average	-	1.34%

Table 5 Change percentage in compressive strength of 'CP' to 'CP120' specimens

Mix	Class	CP120/CP-100%
X-1	C20/25	3.66%
X-2	C25/30	4.61%
X-3	C30/37	-1.54%
Y-1	C20/25	0.00%
Y-2	C25/30	3.15%
Y-3	C30/37	0.49%
Y-4	C40/50	-3.26%
Z-1	C60/75	-0.14%
Average	-	0.87%

compression surfaces smoothed (note in Table 2 that this mixture presents high standard deviation). Although a slight increase of the concrete compressive strength has been noted for specimens with smoothed compression faces, strangely no markedly decreasing on the standard deviation was found.

4.3 Results of cubic specimens which tested immediately after removing from the water and tested after drying in the ambient temperature

The EN 12390-3 (2009) states the compressive strength specimens must be tested immediately after they are removed from the water. While, it comes to a large number of specimens for testing, the specimens may be waiting in the ambient temperature, sometimes, longer than an hour (note that the usually procedure is: the technician removes all specimens from the water at once and then starts compressive strength test specimen by specimen). Therefore, in order to assess whether the waiting time at ambient temperature and humidity influence the compressive strength results, this analysis compares the results of the compressive strength of cubic specimens cast in polyurethane moulds that were 120 minutes waiting at the environmental conditions (T=20±2℃ and RH=60±5%) to be tested 'CP120' with specimens poured in similar moulds that were tested almost immediately after being removed from the water 'CP'. Table 5 shows the percentage changes in the compressive strength from 'CP' to 'CP120' specimens.

Table 6 The relationship between the compressive strength of cylindrical and cubic specimens

Mix	Class	CY/CP
X-1	C20/25	0.98
X-2	C25/30	0.99
X-3	C30/37	0.96
Y-1	C20/25	0.90
Y-2	C25/30	0.98
Y-3	C30/37	0.94
Y-4	C40/50	0.97
Z-1	C60/75	0.97
Average	-	0.96

Table 7 Concrete classification based on test results

Mix	Commercial-class strength	Classification according to Euro-code 2 based on the test results	
		Cylindrical (CY)	Cubic (CP)
X-1	C20/25	C20/25	C16/20
X-2	C25/30	C35/45	C25/30
X-3	C30/37	C40/50	C35/45
Y-1	C20/25	C25/30	C25/30
Y-2	C25/30	C35/45	C30/37
Y-3	C30/37	C35/45	C30/37
Y-4	C40/50	C60/75	C50/60
Z-1	C60/75	C70/85	C55/67

As shown in Table 5, the compressive strength slightly increases for specimens that waited two hours to be tested. However, no clear tendency is observed. In fact, with a much deeper analysis it is observed that low and high strength concrete seems to present opposite behaviours. This might be connected with the concrete surface drying rate. Nevertheless, more tests with higher controlled environmental conditions must be carry out in order to clarify this effect.

4.4 Results of cylindrical specimens versus cubic specimens

Bearing in mind that codes (among others, the Eurocode 2) usually allows to characterize the concrete compressive strength either in cubic or cylindrical specimens, the proposed relationship being $f_c^{cylinder}/f_c^{cube}$=0.80, the measured compressive strength values for cubic (CP) and cylindrical specimens (CY) cast into moulds fabricated of polyurethane are reported in Table 6. As it can be noted in Table 6, the relationship found is far from 0.80. In fact, it is much closer to 1.0 than to 0.80. Solely for one mixture the relationship was 0.90, for the others being mostly around 0.97.

Seeing that the concrete strength class may be classified trough cubic or cylindrical specimens, based on the tests results of Table 2, Table 7 presents the commercial concrete strength classes using the Eurocode 2 (2004) classification trough cylindrical and cubic specimens for each mixture.

Being aware that cubic moulds are the most used in Portugal, as shown in Table 7, one concludes that it is much more advantageous to use cylindrical specimens. It is observed an increase of the concrete strength class from cubic to cylindrical specimens for all mixtures except Y-1. Moreover, X-2, Y-4 and Z-1 (SCC) have raised two classes. Thus, it appears that using cylindrical moulds are accurate and economically compare with polyurethane cubic moulds. Note that the standard deviation in Table 2 is frequently lower for sets of cylindrical specimens, i.e., cylindrical specimens presented higher accurate. Nevertheless, cylindrical specimens are more costly because they need to be smoothed and they are heavier because they require larger volume of concrete.

Table 8 The relationship between the compressive strength of prismatic and cubic specimens

Mix	Class	PR/CIS	PR/CY
Mix	C20/25	0.81	0.92
X-1	C25/30	0.76	0.85
X-2	C30/37	0.89	0.97
X-3	C20/25	0.86	0.99
Y-1	C25/30	0.82	0.90
Y-2	C30/37	0.81	0.90
Y-3	C40/50	0.82	0.91
Y-4	C40/50	0.85	0.93
Z-1	C60/75	0.83	0.92
Average	-	0.81	0.92

4.5 Results of prismatic specimens versus with cylindrical and cubic specimens

The test results in Table 2 show that prismatic specimens (‘PR’) have lower compressive strength in comparison with cubic or cylindrical specimens. It also appears that the prismatic specimens were leading to greater scattered results. Seeing that prismatic mould were fabricated in cast iron, one shall compare values of concrete strength moulded in cast iron cube (‘CIS’) moulds with prismatic specimens (‘PR’). Table 8 shows that relationship. By analysing Table 8, we found an average ratio of 82% which most close to the proposed ratio of 0.80 of the Eurocode 2.

When the relationship between prismatic specimens and cylindrical specimens has been analysed in Table 8, we note that the ratio goes to 0.93. As at the conclusion of Section 4.1 where cubic specimens with 150 mm are compared with cylindrical specimens with 150×300 mm, one can be concluded that the proposed ratio in Eurocode is wrongly being applied between cubic specimens with 150 mm are compared with cylindrical specimens with 150×300 mm. According to the results obtained, one may conclude that ratio of 0.80 is for cube and prismatic specimens with the same base and the total volume of the prism being about 250% of the cube volume.

4.6 Results of specimens with and without E-modulus test

The *E*-modulus test typically is performed in cylindrical

Table 9 The relationship between carrying out and not the *E*-modulus test before the compressive strength test

Mix	Class	CYEM/CY
X-1	C20/25	0.83%
X-2	C25/30	0.00%
X-3	C30/37	1.14%
Y-1	C20/25	0.00%
Y-2	C25/30	-0.27%
Y-3	C30/37	-0.52%
Y-4	C40/50	1.28%
Z-1	C40/50	0.14%
Average	-	0.33%

specimens. Seeing that the *E*-modulus test is non-destructive test, the tested specimen is then normally used to evaluate the concrete compressive strength. Codes do not prohibit reusing the specimen. In fact, the maximum load stress of the *E*-modulus test shall be 30% of the concrete compressive strength. However, several loading cycles are applied (sometimes at several ages) and doubts were raised about the influence of the *E*-modulus test on the value of the compressive strength. Moreover, the *E*-modulus test requires that the compressive strength test is not performed immediately after specimen being removed from water. Thus, in Table 9 are reported the changes found between carrying out and not the *E*-modulus test before the compressive strength test.

Table 9 shows a quite slight increase of the concrete strength (0.33% in average). However, such increase is not clear tendency for all mixtures with differences found being mostly negligible. Besides, specimens that are subjected to the *E*-modulus test are at environmental conditions during the *E*-modulus test and most of results are within the standard deviation. Therefore, it can be concluded that the *E*-modulus test does not affect the compressive strength value of that specimen.

5. Theoretical analysis

5.1 Theoretical analysis of the size effect

Bazant (1984), Kim and Eo (1990), Alsani (2013) proposed the modified size effect law (MSEL, Eq. (2)) by adding the size independent strength $\sigma_o(=\alpha\ f_{ct})$ to the size effect law (SEL) to predict the strength of concrete structures with or without initial cracks and with similar or dissimilar cracks. This concept was also proposed by Bazant (1989, 1993), Bazant and Xiang (1997) with a different approach.

$$\sigma_N(d)=\frac{B\,f_{ct}}{\sqrt{1+d/\lambda_o\,d_a}}+\alpha\,f_{ct} \quad (2)$$

where $\sigma_N(d)$ is the nominal strength, f_{ct} is the direct tensile strength, d is the characteristic dimension, d_a is the maximum aggregate size, and B, λ_o, and α are the empirical constants.

Although the failure mechanism and effect of size on tensile failure have been studied extensively, the behaviour of compressive failure has not been sufficiently studied in comparison. Concrete is a construction material normally used to withstand compressive force. Accordingly, more studies in this field are necessary. Since it is logical to extend the tensile size effect research to compressive failure research, the direct tensile strength f_{ct} used in MSEL must be substituted with the compressive strength of standard cylinder f'_c in the new equation for the prediction of the effect of size on compression. This substitution can be done because, even though the tensile failure mechanism is different from the compressive failure mechanism, the ultimate failure of both is due to the propagation of macro-crack, indicating a localized tension or Mode I failure. Therefore, it is safe to assume that the tensile fracture-based concept can be applied to compressive failure as well. The validity of MSEL was demonstrated by regression analyses on available test data for tensile strength, shear strength, and uniaxial compressive strength.

As an application of MSEL, some studies have been performed on unnotched and notched cylindrical specimens subjected to uniaxial compressive force; on axially-loaded, double-cantilever beams; and on *C*-shaped specimens subjected to flexural compression force. In Eq. (2), the width of crack band l_o is empirically found to be related to the maximum aggregate size d_a (in this study, d_a=11 to 22 mm), e.g., $l_o=\lambda_o d_a$ in which λ_o is an approximate constant with values between 2.0 and 3.0 (Bazant 1984, Kim *et al.* 1999, Kim *et al.* 2000). In the regression analysis, this constant is selected as 2.0, where $l_o=2.0d_a$=20.0 mm. In the previous study (Kim *et al.* 1999), Eq. (3) was proposed to obtain the compressive strength of cylindrical concrete specimens with various diameters and height/diameter ratios. For this purpose, the effects of the maximum aggregate size on the fracture process zone were considered and the concept of characteristic length was newly introduced. The method to determine the characteristic length is derived and explained by Kim and Eo (1990)

$$\sigma_N(h,d)=\frac{0.4\,f'_c}{\sqrt{1+(h-d)/5}}+0.8\,f'_c \quad (3)$$

where the height of cylinder specimen h and the diameter of cylinder specimen d are in cm. Eq. (3) was compared to the ASTM standard (2000), and it was noted that the prediction values of Eq. (3) are less than those of the ASTM standard, but the difference is minimal. In the following sections 5.2 to 5.6, proposed models are based on revised version of the current models by Aslani (2013).

5.2 Size effect for cubic compressive strength

Fig. 1(a) shows the comparison measured compressive strength versus to predicted compressive strength for cubic specimens. Regression analyses were conducted to measure the compressive strength of the cubes, Eq. (4) was obtained, and the results are graphed and shown in Fig. 1(a).

$$f'_{c,cu}(d)=\frac{1.17\,f'_{cu}}{\sqrt{1+d/l_o}}+0.55\,f'_{cu} \quad (4)$$

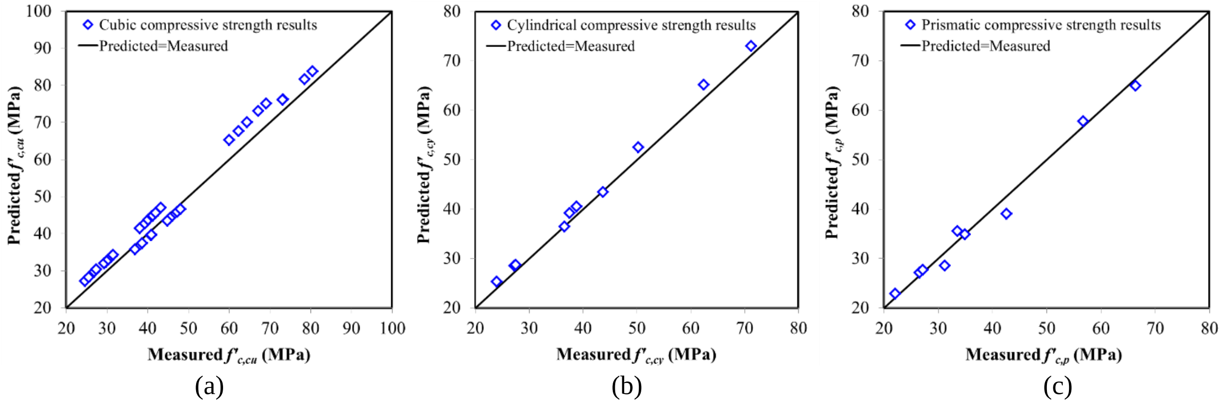

Fig. 1 Comparison of measured compressive strength versus to predicted: (a) cubic, (b) cylindrical and (c) prismatic

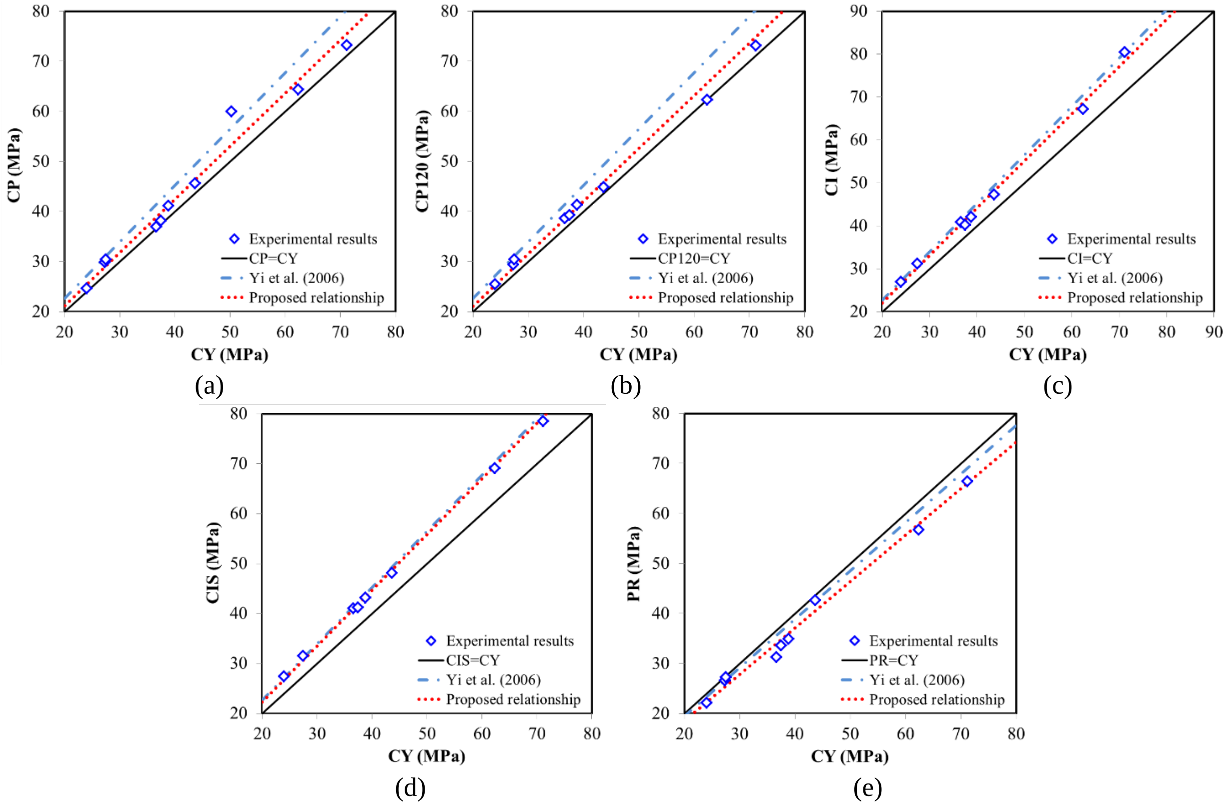

Fig. 2 Comparison of measured CY compressive strength versus to: (a) 'CP', (b) 'CP120', (c) 'CI', (d) 'CIS' and (e) 'PR'

where f'_{cu} is the cubic compressive strength in MPa, size of the cube d is in cm, l_o=2.0d_a and d_a is the maximum aggregate size.

5.3 Size effect for cylindrical compressive strength

Eq. (5) was obtained from least squares method regression analyses for cylinders. Fig. 1(b) shows the comparison measured compressive strength versus to predicted compressive strength for cylindrical specimens. In this study, it is concluded that the strength ratio approaches a limit with an increasing diameter *d*.

$$f'_{c,cy}(d) = \frac{0.49\, f'_{cy}}{\sqrt{1 + d / l_o}} + 0.82\, f'_c \qquad (5)$$

where f'_{cy} is the cylindrical compressive strength in MPa, size of the cube d is in cm, l_o=2.0d_a and d_a is the maximum aggregate size.

5.4 Size effect for prismatic compressive strength

Eq. (6) was obtained from least squares method regression analyses for cylinders. Fig. 1(c) shows the comparison measured compressive strength versus to predicted compressive strength for prismatic specimens. In this study, it is concluded that the strength ratio approaches a limit with an increasing diameter *d*.

$$f'_{c,p}(d) = \frac{1.0\, f'_{p}}{\sqrt{1 + d / l_o}} + 0.55\, f'_c \qquad (6)$$

where f'_p is the prismatic compressive strength in MPa, size of the cube d is in cm, l_o=2.0d_a , and d_a is the maximum aggregate size.

5.5 Relationship between specimen shapes

Yi *et al*. (2006) presented conversion factors with sizes and shapes of the specimen for normal- and high- strength concrete. The conversion factors for cylinder specimens with 150×300 mm dimensions versus cube specimens with 150 mm dimensions and prism specimens with 150×150×375 mm dimensions are 0.88 and 1.03, respectively. Fig. 2 shows plot the cylinders' versus the cubes' and the prism's compressive strengths for the represented specimen sizes. In these figures, solid lines and dashed lines indicate the best-fit lines obtained from linear regression analyses, Yi *et al*. (2006) prediction and the lines of equality Y=X, respectively. These figures shows the conversion factors for 'CY' versus 'CP', 'CP120', 'CI', 'CY', and 'PR' are 0.94, 0.95, 0.91, 0.89, and 1.08, respectively. These results show that cubic specimens using polyurethane moulds increased the conversion factors and the results for cubic specimens using the cast iron moulds are similar to Yi *et al*. (2006) results.

6. Conclusions

This investigation was mainly undertaken to evaluate the compressive strength of concrete mixes having different percentages of volcanic aggregates from Madeira Island in Portugal. The following conclusions can be drawn from this experimental and theoretical study:

- The material of which mould is manufactured influences the compressive strength result of concrete. In this study, at the age of 28 days, the cast iron moulds show higher compressive strength results in compassion with the polyurethane mould. This fact might be related to the temperature that the specimen reaches before demoulding, but more research is needed, including the implementation of compressive strength tests at younger ages, to document the hypothesis.
- Apparently, the time between removing a concrete specimen from water and the time when it carries out the compression test does not lead to significant changes in strength results.
- Size effect of the concrete based on the specimen size and shape difference is present. The size effect for cubes and prisms is stronger than cylinders. The world widely used relationship of 0.8 is satisfactory between cubic and prismatic specimens but totally inadequate between cubic and cylindrical specimens.
- The E-modulus test does not affect the compressive strength value of that specimen.
- To obtain the concrete compressive strength, model equations applicable to cylinders, cubes, and prisms are suggested. In addition, correlations between compressive strengths with size and shape of the specimen are investigated. Additionally, to obtain the concrete compressive strength of cylinder from other specimen shapes, model equations commonly applicable to both specimen shapes (i.e., (1) cylinders and cubes and (2) cylinders and prisms) are suggested.

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