IF CRASC '15
III Convegno di Ingegneria Forense
VI Convegno su Crolli, Affidabilità Strutturale, Consolidamento
SAPIENZA UNIVERSITA' DI ROMA, 14-16 MAGGIO 2015

TESTING LOW STRENGTH CONCRETE OF COLLAPSED FRAME BUILDINGS

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ABSTRACT
Within the scope of measurement of *in-situ* material properties, the paper presents results of two studies carried out by the Authors for forensic investigations of concrete properties in existing reinforced concrete frame structures collapsed during the 2009 Aquila earthquake. The two edifices were built in the 1960s; the results provide data on low-strength material property measurement. Cores were extracted: 53 specimens in two series for the first building and 16 in the second. Compression tests were carried out following EN12390-3, providing data on density, compression strength and ultrasound velocity. Non-Destructive Testing with SONREB measurements were also carried out in the first building. The test results are analyzed and discussed in relation to the design documents and the Italian code specifications at the time of the design of the building. The conclusions show that the concrete quality was very poor in relation to low quality construction practices.

1. INTRODUCTION

The study of existing structures requires the determination of material properties (ISO 13822, 2010). A part of the concrete structures built in the fifties and sixties in Italy and other areas of Europe are affected by poor concrete properties, related to low-quality materials and poor construction practices. While some infrastructure construction was of good quality (Mezzina et al., 2008), this problem affects in particular residential buildings. The testing of concrete cores is the widely accepted method for determining *in situ* strength (Neville, 1970; EN 12390-3), in combination with the use of non-destructive methods (RILEM, 1993). The paper describes their application for low-strength concrete, presenting results of experimental studies of concrete properties in two existing reinforced concrete frame structures collapsed during the April, 6 2009 L'Aquila seismic event (Mulas et al., 2013; 2014).
During the 2009 earthquake, the "Casa dello Studente" building suffered a partial collapse of the North wing. The building located in via D'Annunzio (D'Annunzio street) totally col-

lapsed. In the following these are indicated as first and second case study. For the first case study (Figure 1a, b), two wings of the building remained standing during the event. The third wing experienced a soft storey at ground floor, and a partial collapse on all floors leaving standing the columns and beams of the storey below ground (Mulas et al., 2013). In the second case study (Mulas et al., 2014) the whole building collapsed (Figure 1c, d). The removal of the debris showed the columns stubs remaining standing at the basement floor. This part of the building contained the car parking garages. These dramatic events lead to the loss of human lives in both cases: the “Casa dello studente” was a building adapted to college students home, while the construction in via D’Annunzio was a residential building. Both edifices were designed and built in the early sixties.

Figure 1: “Casa dello studente”, (a-b) soft-storey of the North wing. Via D’Annunzio, (c-d) before and after the earthquake.

Aim of this work is to present the data gathered by the Authors with the occasion of forensic investigations, showing the features of low-strength and bad-quality concrete. The issues considered include strength results from cores, with the material density and ultrasound velocity propagation correlated to strength. The determination of the quality of the construction process from the material properties is discussed. The test results presented here were gathered in three campaigns carried out on the two buildings (Mulas et al., 2013; 2014). The test results are analyzed and discussed in relation to the design documents and the Italian code specifications at the time of the design of the building.

2. TEST RESULTS

After the collapse, in the first case study two experimental campaigns were carried out including concrete cores, rebound hammer and ultrasonic tests (SONREB); in the second case study only cores were drilled and tested for compression strength. In the following the core strength results are reported and analyzed, together with the density of the concrete.

2.1. Core test results

For the first case study, 52 cores were drilled, 42 from columns in the still standing parts of the building and 10 from columns and beams extracted from the debris of the floors that collapsed. This first experimental campaign was carried out in 2009, as a part of a thorough investigation aiming to understand the reason for collapses of reinforced concrete buildings during the earthquake. The concrete cores were subject to the standard compression strength test according to UNI-EN 12390-3 (CEN, 2009) and ultrasonic pulse velocity tests according to UNI EN 12504-4 (CEN 2004). In addition, non-destructive tests were carried out on 32 columns, 27 of which coincided with columns tested with cores (see section 2.3). Within the compression tests the failure modes of 7 cores were non satisfactory; hence in the following reference is made to the remaining 45 cores. The relevant data, including the core mark, the floor of the building where the core was drilled, and the results in terms of density, core strength, strength measured through SONREB and ultrasonic speed are listed in Table 1a.

The mean *in situ* cylinder compressive strength $f_{cm,is}$ value was 13,3 MPa; Table 1b lists the statistical parameters of interest herein. The coefficient of variation COV, computed as $\sigma/f_{cm,is}$, is equal to 0,29. The characteristic "in situ" cylinder strength $f_{ck,is}$ is computed as:

$$f_{ck,is} = f_{cm,is} - k_2\, \sigma = 13{,}3 - 1{,}48 \times 3{,}89 = 7{,}5 \text{ MPa} \qquad (1)$$

In equation (1) k_2 is a statistical coefficient for the calculation of $f_{ck,is}$, when the characteristic value is estimated on the basis of a sample of test results. The value k_2= 1,48 is indicated by EN 13791 when the sample is made of at least 15 test results. The parameter σ is the standard deviation of $f_{c,is}$. The strength values are very low; according to the classes defined in EN 13791, the standard class is C8/10, lower than the class required in design.

Mark	Floor	Density (Kg/m^3)	Core strength f_c (MPa)	SONREB Rc (MPa)	US speed (m/s)
S 3	4	2206	10,0		3219
S 1	-1	2173	7,7		3182
S 4	3	2171	13,9		3240
S 5	2	2216	12,4		3774
S 6	1	2261	27,0		4357
S 7	0	2148	9,9	14,4	3148
S 2G	-1	2201	7,6	17,0	3328
S 8	0	2173	14,3	17,3	3571
S 9	-1	2169	10,8	14,2	3399
S 10	-1	2146	16,0	17,5	3624
S 11	0	2182	12,1	17,9	3500
S 12	1	2167	9,7	16,3	3252
S 13	1	2177	13,2	16,4	3488
S 15	1	2232	10,4	20,3	3612
S 16	1	2208	17,4		3671
S 17	2	2149	11,2		3399
s 18	2	2183	14,0	20,6	3632
S 19	2	2200	16,8		3824
S 20	0	2181	14,3	20,1	3562
s 25	3	2210	14,0		3612
S 26	4	2186	14,1		3649
S 27	4	2185	14,7	22,3	3737
S 22	0	2134	9,1	19,2	3398
S 24	3	2134	9,7	15,53	3228
S 29	4	2167	18,2	24,17	3559
S 30	-	2208	19,6		3852
S 31	3	2125	10,51	18,48	3250
S 32	3	2200	13,1		3312
S 35	2	2173	14,32		3483
C 36	2	2138	13,3	22,53	3220
S 38	-2	2268	16,6		3962
RC1	-	2169	10,1		3333
RC2	-	2212	8,4	17,15	3247
RC3	-	2204	13,5		3730
RC4	-	2173	12	18,83	3519
RC6	-	2228	13,21		3725
G 3	-1	2093	11,5	15,91	3182
G 4	-1	2194	11	17,22	3197
G 5	-1	2197	24,7	27,15	3715
G 6	-1	2214	16,5	19,01	3521
G13	-	2191	11,21		3287
G14	-	2232	14,8		3462
G17	-	2162	11,01		3150
G18	-	2179	12,2		3400
G19	-	2154	11,1		3247

Table 1a – “Casa dello Studente”, first campaign.

The interpretation of compression tests on cores of low strength concrete must consider the possible damage caused by drilling. This is recalled in EN13904; ACI(2010) quantifies the strength reduction with a coefficient of 1/0,94 = 1,06 to be applied on the value for strength obtained, as shown in the last two lines of Table 1b.

	Density (Kg/m^3)	fc' (MPa)
Mean value	2180,0	13,3
Standard Dev. (MPa)		3,9
COV		0,29
Characteristic value (MPa)		7,5
Minimum (MPa)		7,6
Maximum (MPa)		27,0
Core drilling (ACI 214.4R-10)		
Amplification factor	1,06	
Mean value (MPa)		14,1
Characteristic value (MPa)		8,0

Table 1b – “Casa dello Studente”, Statistical results on core test results.

A second testing campaign in the “Casa dello Studente” was carried out in 2011 to check the results of the previous tests. A sample of 8 cores was selected choosing the 5 columns with the lowest values of the previous series of cores, and the 2 columns with the highest values. The former were chosen to check if the cores taken from those columns had been damaged by cracking or by the specimen preparation. The core drilling was preceded by non-destructive tests.

The results of all tests, listed in Table 1c, were higher than in the previous campaign with $f_{cm,is}$=16.5MPa and σ = 5.1MPa ($f_{ck,is}$=8.9 MPa). The values of strength and density of the second sample agreed with the previous sample. It was concluded that the cores with the lowest values in the first sample were damaged.

Mark	Density (Kg/m3)	fc' (MPa)
N1	2166	13,4
N2	2246	23,1
N3	2256	9,3
N4	2190	18,6
N5	2242	22,3
N6A	2210	15,2
N6B	2207	19,0
N7	2144	11,0

Table 1c – “Casa dello Studente”, second campaign.

In the second case study (D'Annunzio Street) the experimental campaign was carried out based on 16 concrete cores taken from the columns (Table 1a). To establish the strength of the in-situ cast concrete, the concrete cores were subject to the standard compression strength test according to UNI-EN 12390-3, including the measurement of density. Table 2b lists the statistical parameters of interest herein. The mean cylinder compressive strength $f_{cm,is}$ value is 14,1 MPa. The coefficient of variation COV, computed as $\sigma/f_{cm,is}$, is equal to 0,39. The characteristic "in situ" cylinder strength $f_{ck,is}$ can be computed as:

$$f_{ck,is} = f_{cm,is} - k_2\,\sigma = 14{,}1 - 1{,}48 \times 5{,}4 = 6{,}0 \text{ MPa} \qquad (2)$$

with the same meaning for symbols as in Equation 1. The strength values are low, also in this case; according to the classes defined in UNI-EN 12390-3 the standard class is C8/10, lower than the class required in design.

Mark	Density (Kg/m3)	fc' (MPa)
C1	2292,7	12,4
C2	2237,8	11,1
C3	2166,1	9,8
C4	2232,7	10,4
C5	2243,9	15,2
C5A	2333,8	15,8
C7	2282,9	10,1
C8	2329,6	26,7
C9	2245,4	16,4
C10	2322,1	20,6
C11A	2294,4	22,6
C12	2151,6	5,9
C13	2195,7	11,6
C14	2176,4	15,0
C15	2179,2	9,6
C16	2244,5	12,0

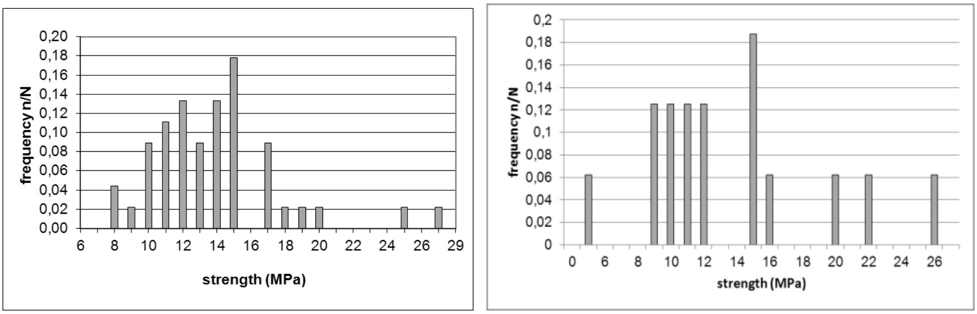
	Density (Kg/m3)	fc' (MPa)
Mean value	2245,5	14,1
Standard Dev. (MPa)		5,4
COV		0,39
Characteristic value (MPa)		6,0
Minimum (MPa)		5,9
Maximum (MPa)		26,7
Core drilling (ACI 214.4R-10)		
Amplification factor	1,06	
Mean value (MPa)		14,9
Characteristic value (MPa)		6,4

Table 2: Via D'Annunzio: left, (a) cores results; right (b) Statistical results on core test data.

2.2. Strength and density

The histograms of strength results for the two case studies (Figure 2) show wide dispersion of results that can be put in relation with poor construction procedures (Bungey, 1998). The coefficients of variation (0,29 and 0,39) are in the typical range for such low-quality material. The presence of different peaks in the distribution for the Casa dello Studente indicates non uniform production processes for the different samples of material. The shape of the two histograms are similar, with higher frequency values to the left of the peak (conventionally defined as "hump and tail" shape).

The results can be explained in terms of a low-quality construction process, concrete mixing casting and curing. A possible situation in the time of the construction in this geographic region and for such a size of building, would have been a small mixer providing several batches of concrete, with rather variable composition and properties for each one. The amount of water in the mix would be dependent on several contingent factors. Also the curing condition would easily be rather poor and variable.



(a) "Casa dello Studente" (b) via d'Annunzio

Figure 2. Histograms of strength results from core compression tests.

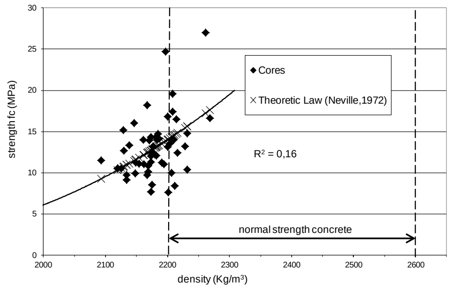
For the "Casa dello Studente" it must be noted that the concrete density was below 2200 Kg/m^3 for all specimens, with a mean value around 2180 Kg/m^3 (Figure 3a). Most values are out of and below the range considered for normal strength concrete.
An interpretation is provided by correlating strength and density measurements. The increase of strength with density shown in the results (Figure 3a) is coherent with a theoretical model (Neville, 1972), considering the variation of strength with the compaction of concrete for a given mix-design. For these results, the coefficient of determination R^2 of the model in Figure 3a was computed according to the well-known expression:

$$R^2 = 1 - \sum_i \left(f_{ci} - f_{ci}^{mod}\right)^2 \Big/ \sum_i \left(f_{ci} - f_{cm}\right)^2 \quad (3)$$

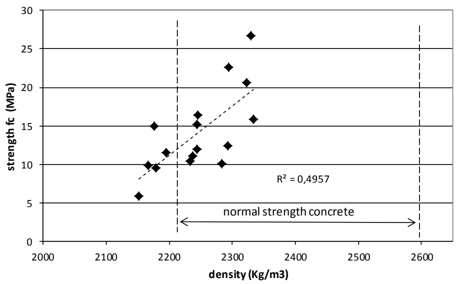
where f_{ci} = measured values; f_{ci}^{mod} = modelled values; f_{cm} = mean value of measured strength. The values of R^2, equal to 0.16 in the first case is very low due to the high scatter in the measured values of strength related to density. The scatter measured by R^2 in Figure 3 can be considered the consequence of a poor construction process with low control in the mix-design and curing.

For Via D'Annunzio the correlation of strength with density is shown in Figure 3b. The concrete density mean value is 2245 Kg/m^3. All values are in the lower part of the range considered for normal strength concrete (2200-2500 kg/m^3), with 31% of the values out of this range, below 2200 kg/m^3. The value of R^2 with respect to a linear fit, equal to 0.459, is relatively low due to the high scatter in the measured values of strength related to density. Again this can be considered the consequence of a poor construction process with low control in the mix-design and curing.
Bad construction often results in high porosity in the concrete because of high water cement ratios, caused by the addition of water in the mix to obtain workability on site. This can be

measured by the density and was observed in the porosity of the cores.



(a) “Casa dello studente” (Mulas et al. 2013)



(b) via d’Annunzio (Mulas et al., 2014)

Figure 3. Strength results in core tests correlated to density.

The variation of strength with ultrasonic velocity measurements in the cores is depicted in Figure 4. The results agree with data in the literature on low-strength concrete (Braga et al. 1990); low velocity values are in accordance with the low strength. The coefficient of determination R^2 of the linear fit in Figure 4 is 0.54; this low value is related to the scatter of the measured values. Ultrasound velocity propagation is also related to the material density.

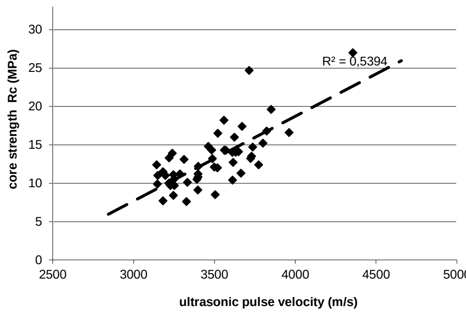


Figure 4. “Casa dello Studente”: ultrasound velocity in cores vs concrete strength (Mulas et al 2013).

2.3. Non-destructive testing

In the first case study non-destructive tests were carried out on 32 columns, 27 of which coincided with columns tested with cores (see section 2.1). Measurements are made of ultrasound velocity propagation and rebound hammer test results. The relations correlating these measurements to strength were calibrated on the basis of the core results. The strength values obtained with the SONREB method (RILEM, 1993) are in agreement with the destructive tests, as shown in Figure 5. The mean values of strength at each story of the building, not listed here, agree with the sample mean, and no trend can be recognized from the top to the bottom indicating that the cores were not affected by earthquake induced damage. The mean strength and standard deviation of the cores taken from members of the collapsed part of the building agree with the results of the sample.

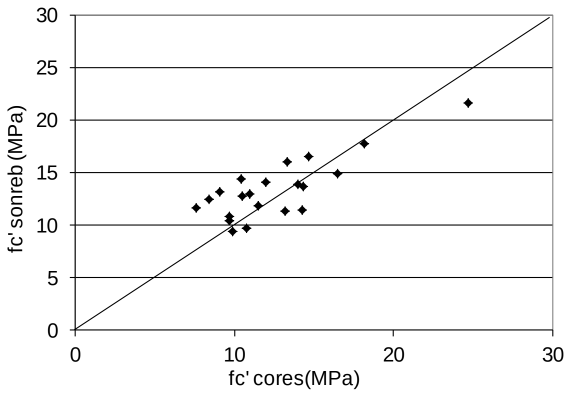


Figure 5. " Casa dello Studente", SONREB results.

2.4. Reinforcement samples

Four steel samples were taken from the collapsed part of the first building, three for smooth reinforcement and one deformed bar. The tension tests for the smooth bars measured mean yield strength equal to 312 MPa with a rather high scatter (range of values 281-344 MPa). Average elongation at failure was 32% (28-36%). Eight steel samples were taken from beams and columns of the collapsed part of the second building, made of smooth reinforcement, with average diameter around 18 mm. The tension tests measured mean yield strength 388 MPa (range of values 359-430 MPa), mean strength 554 MPa (542-590 MPa), average elongation at failure 27% (21-32%). These results are in good agreement with design values in both cases.

3. DESIGN REQUIREMENTS AND CODE SPECIFICATIONS

Based on the tests, characteristic values of *in situ* cylinder strength f_{ckis} equal to 7,5 and 6,0 MPa respectively have been determined on the basis of EN13791. The corresponding cubic values are $R_{ck,is}$ = 9,0 and 7.2 MPa. These values, according to EN13791, correspond to C8/10 class concrete for the "Casa dello Studente" and below this for via D'Annunzio. This indicates poor concrete quality respect to modern standards and to the requirements of the Code of the time of design of the building, as will be reported in the following.
The design specifications in the two case studies made use of allowable stresses, as established by a "*Regio Decreto"* in 1939. The code was still in force at time of design of both buildings. The value of allowable stress was not reported in the design documents, but the stresses calculated as load effects were declared to be lower than the allowable stress of the prescribed concrete. The maximum stresses calculated were 67 Kg/cm^2 in the first case and 66 Kg/cm^2 in the second. In addition the calculations were carried out without considering shrinkage and temperature effects; in this case the 1939 code specified the allowable stress could not be higher than 75 Kg/cm^2. Hence the allowable stress falls between 67 and 75 Kg/cm^2 for the "Casa dello Studente" and 66 and 75 Kg/cm^2 for via D'Annunzio.
The 1939 code prescribed a constant control of the quality of concrete, by preparing and testing standard cubes, to use allowable stress higher than 50 Kg/cm^2; the allowable stress was calculated as one third of the 28-day concrete strength σ_{r28}. This strength had to be determined as the average of the three higher values obtained preparing four standard cubes, tested for strength. Using an allowable strength in the range 67-75 Kg/cm^2 meant that the strength σ_{r28} for each sample of four cubes had to be greater than 201-225 kg/cm^2, the minimum threshold for σ_{r28}.
To determine the class of concrete strength required by the design, a minimum average strength of the sample σ_{r28} equal to 201-225 kg/cm^2 indicates approximately that the value of concrete cubic characteristic standard strength f_{ck} would be around 235-260 kg/cm^2.
The in-situ values with good construction would hence be around $R_{ck,is}$ = 20-22 MPa – here obtained multiplying by the 0,85 factor according to EN13791. This means that results from testing the concrete *in situ* should indicate a class C16/20 or C20/25. The difference between the measured $R_{ck,is}$ = 9,0 and 7.2 MPa (C8/10 or less) and the required C16/20 or C20/25 indicates the poor quality of the in situ concrete.

4. CONCLUSIONS

The results of two experimental studies of *in situ* concrete properties have been presented, carried out in reinforced concrete frame structures where dramatic failures took place because of seismic loading.
Built during the 1960s for residential and office use, the two case studies may be considered representative of many similar constructions, hence arising concern for such category of buildings and the need for careful assessments starting from the material properties.
The testing of cores together with SONREB nondestructive testing revealed very low characteristic concrete strength, with high dispersion of test results. The strength has been corre-

lated with density and ultrasonic wave propagation.
The results collected build up a database, providing information on density, compression strength and ultrasound velocity. The analysis of the data suggests that poor construction techniques and materials could have played a significant role for the two failures, even though a final judgment on the causes triggering the failure requires the analysis of several other factors. We can list among them the building configuration and the geometry of the structure, the correspondence between design load and loads acting on the built edifice, the amount and detailing of reinforcement, both longitudinal and transverse, the presence of modifications to the structure in subsequent refurbishment works, the interaction with near-by buildings, foundation settlements. In each structural collapse all these factors must be carefully considered.

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