

# 1 **Chemical and mechanical properties of 70-year-old concrete**

2 Ph.D. D.Sc., Eng., **Andrzej Ambroziak**

3 The Faculty of Civil and Environmental Engineering, Gdansk University of Technology  
4 11/12 Gabriela Narutowicza Street, 80-233 Gdańsk

5 Corresponding author: [ambrozan@pg.edu.pl](mailto:ambrozan@pg.edu.pl), job title or position: Associate Professor

6 Ph.D. Eng. **Elżbieta Hausteina**

7 The Faculty of Civil and Environmental Engineering, Gdansk University of Technology  
8 11/12 Gabriela Narutowicza Street, 80-233 Gdańsk

9 [hausteina@pg.edu.pl](mailto:hausteina@pg.edu.pl), job title or position: Assistant Professor

10 M.Sc. Eng. **Jarosław Kondrat**

11 The Faculty of Civil and Environmental Engineering, Gdansk University of Technology  
12 11/12 Gabriela Narutowicza Street, 80-233 Gdańsk

13 [jarko@pg.edu.pl](mailto:jarko@pg.edu.pl), job title or position: Specialist

14 **Abstract:** The aim of this research is to determine the durability and strength of concrete  
15 continuous footing based on the chosen mechanical, physical and chemical properties of the  
16 concrete. The presented investigations are a part of opinions from experts on the bearing  
17 capacity of concrete continuous footing and the possibilities of carrying additional loads and  
18 extended working life. The cylindrical specimens were taken from continuous footing by a  
19 concrete core bore hole diamond drill machine. The properties of old concrete are compared  
20 with present and old standard requirements and guidelines. Large dispersions of the  
21 cylindrical compressive strength (6.9 MPa to 29.3 MPa), density (1750 kg/m<sup>3</sup> to 2100 kg/m<sup>3</sup>)  
22 and water absorption (5% to 14%) were observed. A short literature survey concerning old  
23 concrete properties is also given.

24 **Keywords:** Structural concrete; core-drilled samples, material characterization, mechanical  
25 properties; chemical properties

26

## 27 **Introduction**

28 Concrete is one of the most popular materials used in civil engineering. In present  
29 standards (see, e.g., CEN 2013), the intended working life of concrete in normal building  
30 structures is assumed to be at least 50 years. Standards for concrete structure design indicate  
31 the durability recommendations for concrete properties and other limiting values to resist  
32 environmental influences. By providing improved compressive strength classes, water-  
33 cement ratios, cement weights, and cover of rebars, to name a few, the designed working life  
34 of reinforced or prestressed concrete structures may be raised to at least 100 years.

35 The design process of new reinforced or prestressed concrete structures is very well  
36 specified by standards (see e.g., ACI 2014 or CEN 2004). In this domain, the designers have  
37 considered the mechanical properties of concrete or reinforcement concrete for load capacity  
38 requirements and intended working life. However, when designers must use opinions from  
39 experts on old reinforced concrete structures, access to both structural design and structural  
40 analysis is required. Additionally, the range of strength tests should be specified and  
41 performed to determine the actual material properties of structural elements. When the  
42 structural design (e.g., drawings) and structural analysis (e.g., static calculations) are  
43 inaccessible, the opinions from experts are difficult to execute. To specify the durability and  
44 bearing capacity of concrete construction, additional mechanical, chemical and physical tests  
45 should be carried out.

46 The preservation and protection of old buildings require necessary information about  
47 their main structure durability to ensure safe operational use by inhabitants or other people.  
48 A proper assessment of the mechanical properties of old concrete using laboratory tests  
49 strongly impacts the level of precision in an expert opinion or economical design. The  
50 investigation of old concrete structures has been considered not only by engineers but also  
51 by scientists. Qazweeni and Daoud 1991 examined the physical, mechanical and chemical  
52 properties of concrete core specimens taken from a 20-year-old office building. The authors

53 concluded that the used concrete had low density, high absorption ratios and voids.  
54 Furthermore, the observed failure of the concrete structure was caused by chloride and  
55 carbonation attacks. Muntean et al. 2008 investigated the mechanical properties of old  
56 concrete constructions that underwent the carbonation process. The main conclusion was that  
57 the increased content of belite in the Portland cement had a positive influence on concrete  
58 durability, particularly upon the rate of carbonation. Sena-Cruz et al. 2013 studied the  
59 mechanical and chemical properties of structural materials of a reinforced concrete bridge  
60 built in 1907. Laboratory tests showed a high porosity in the concrete (7-10%); nevertheless,  
61 a concrete strength class greater than C30/37 and average modulus of elasticity  
62 (approximately 30 GPa) were determined. Gibas et al. 2015 examined the compressive  
63 strength of cored concrete specimens, chloride penetration and the rate of water absorption  
64 of an unfinished concrete structure of a nuclear power plant, which was exposed for over 30  
65 years to environmental conditions. The authors noted that the compressive strength was  
66 above 60 MPa with low carbonation depth; however, the rate of water absorption and the  
67 coefficient of chloride migration showed a large dispersion of concrete quality. Blanco et al.  
68 2016 examined the chemical reactions leading to the degradation of a 95-year-old concrete  
69 dam manufactured with sand-cement as a binder. The results revealed that the concrete in the  
70 main dam body exhibited satisfactory mechanical properties with a pH of over 10 despite the  
71 degradation of approximately 15 cm of the superficial dam layer. Dawczynski and Brol 2016  
72 performed mechanical and chemical laboratory tests for 40-year-old reinforced concrete  
73 precast bridge beams. Šimonová et al. 2017 performed three-point bending fracture tests on  
74 structural concrete from a 1970s railway station and determined the modulus of elasticity,  
75 fracture toughness, toughness and fracture energy. Pettigrew et al. 2016 performed laboratory  
76 testing of nearly 50-year-old concrete bridge girders to specify the effective prestress,  
77 flexural capacity, and deck punching shear strength.



78 Scientific and technical papers about old concrete structures concern not only buildings  
79 but also bridges, dams and tunnels. The range of mechanical and chemical tests applied in  
80 the presented investigations are generally determined by the type of analyzed concrete  
81 structure and its complicated character. A full-scale investigation of old concrete construction  
82 elements is hardly ever performed (e.g., for a decommissioned bridge, see Pettigrew et al.  
83 2016). Usually, concrete samples are taken from old construction for experimental testing.  
84 Nevertheless, it can be seen that the subject of old concrete structures is taken into  
85 consideration in many engineering and scientific investigations where different  
86 methodologies and laboratory tests are performed to specify their properties. The authors are  
87 aware of the fact that a review of scientific and engineering research applications of old  
88 concrete is limited and pay attention to the chosen studies only.

89 A lack of universal tools for describing old concrete behavior implies new investigations  
90 and laboratory tests. The aim of this research is to determine the durability and strength of  
91 concrete continuous footing based on the chosen mechanical, physical and chemical  
92 properties of concrete. Continuous footing is a 70-year-old structural element. The  
93 investigation was a part of an opinion from an expert on the bearing capacity of concrete  
94 continuous footing and the possibilities of carrying additional loads and having an extended  
95 working life.

96

## 97 **Materials and Design**

98 The proposed research addresses experiments performed to determine the selected  
99 mechanical, physical and chemical properties of 70-year-old concrete core samples. The  
100 cylindrical specimens were taken from the continuous footing of an office building by a  
101 concrete core bore hole diamond drill machine (see Fig. 1) from locations with similar  
102 geometrical and boundary conditions. The thickness of the continuous footing was



103 approximately 70 cm, and the top surface was at an elevation of +13.2 masl (meters above  
104 sea level). The altitude under the surrounding ground level was (+14.0 to 14.15 masl). The  
105 office building was built in the early 1950s in Gdansk, Poland. The structural analysis was  
106 carried out by Prof. W. Bogucki in March 1948.

107 It should be noted that collection of the core samples for uniaxial tensile tests was  
108 difficult. Many cylindrical samples with lengths equal to twice the diameter were damaged  
109 during the diamond drilling process. The core samples with visible defects after core drilling  
110 were excluded from laboratory tests. In the investigated concrete, continuous footing coarse  
111 aggregates with very coarse gravel, cobbles or layers of low strength concrete were  
112 observed. Requirements from the ASTM C31 standard (ASTM 2018) state that the cylinder  
113 length shall be twice the diameter and diameter shall be at least 3 times the nominal  
114 maximum size of the coarse aggregate for old concrete structure. This requirement is often  
115 impossible to fulfil for old concrete structures.

116 In the present investigation, two types of cylindrical samples were prepared from the  
117 exploratory bore holes:

- 118 • eleven samples of type A with diameter  $D$  equal to approximately 140 mm and length  $L$   
119 equal to approximately 280 mm (length to core diameter ratio  $L/D=2$ ) and
- 120 • ten samples of type B with diameter  $D$  equal to approximately 140 mm and length  $L$   
121 equal to approximately 140 mm (length to core diameter ratio  $L/D=1$ ).

122 The dimensions of the concrete cores were taken according to standard EN 12504-1 (CEN  
123 2009), where the preferred length/diameter ratios are 2.0 if the strength results are to be  
124 compared to the cylindrical strength and 1.0 if the strength results are to be compared to the  
125 cube strength of  $15 \times 15 \times 15$  cm concrete specimens. At the time when the structural analysis  
126 of the building was performed, use of the Polish standard PN-B-195 (



127 PKN 1945) was mandatory for the design of reinforced concrete structures. The designers  
128 and contractors of concrete works had to follow the guidelines to obtain particular strength  
129 characteristics for the concrete. Table 1 presents concrete strength depending on the amount  
130 of cement in 1 m<sup>3</sup> of finished concrete and on the degree of liquidity and the ratio of sand-to-  
131 gravel or crushed stone according to guidelines given in standard PN-B-195 (

132 PKN 1945). The concrete strength was specified from 0 (zero) MPa (0 kg/cm<sup>2</sup>) to 19.62  
133 MPa (200 kg/cm<sup>2</sup>). A zero concrete strength was defined to emphasize that the amount of  
134 water should be limited in mix design. The present standards or guidelines define  
135 requirements for the water-to-cement ratio without mentioning zero-strength concrete.

136 In the structural analysis, the permitted strength for concrete was 19.62 MPa (200 kg/cm<sup>2</sup>,  
137 determined for cylindrical samples) and was 137.34 MPa (1400 kg/cm<sup>2</sup>) for steel. The  
138 structural designer in 1948 adopted the highest strength for the concrete defined by standard  
139 PN-B-195 (

140 PKN 1945), as shown in Table 1. The mix design of the old concrete requires 400 [kg]  
141 Portland cement in 1 m<sup>3</sup> of concrete mix and contents of approximately 600 [kg] sand and  
142 approximately 1200 [kg] gravel with rammed consistency. The production technology was  
143 probably based on portable concrete mixers with handmade proportions of concrete  
144 components. The rammed consistency can refer to present specification as a consistency with  
145 a lower slump in a slump test (see, e.g., ASTM 2015).

146 In accordance with the present European EN 206 standard (CEN 2013), the  
147 environmental conditions XC2 (wet, rarely dry) for reinforced concrete continuous footing  
148 completely abandoned taking soil into account. For this exposure class, a minimum designed  
149 concrete C25/30 (with 25 MPa of characteristic cylindrical compressive strength and 30 MPa  
150 of characteristic compressive cube strength at 28 days) should be assumed for the present  
151 European structural design of continuous footing.

## 152 **Laboratory tests**

### 153 *Tests of water absorption*

154 The water absorption tests were carried out following Annex G - EN 13369 (CEN  
155 2001b). To measure the water uptake capacity of concrete samples, the specimens were  
156 soaked in drinking water to a constant mass and then oven dried in a ventilated drying oven  
157 at  $105 \pm 5^\circ\text{C}$  to a constant mass. A water absorption test for concrete can estimate the  
158 permeability and porosity (pore structure) of concrete samples (see, e.g., Kelham 1988).  
159 However, mercury intrusion porosimetry (MIP) may also be used to investigate the pore  
160 structure of cement-based materials (see, e.g., Ma 2014). It is known that the concrete pore  
161 structure is an important factor that influences concrete durability and resistance against  
162 carbonation and chloride migration (see, e.g., De Schutter and Audenaert 2004).  
163 Additionally, the ASTM C1585 standard (ASTM 2013) emphasizes that the water absorption  
164 depends on concrete mixture proportions, presence of chemical admixtures and  
165 supplementary cementitious materials, composition and physical characteristics of the  
166 cementitious component and of the aggregates, entrained air content, and type and duration  
167 of curing.

168 The water absorption results versus dry density are presented in Fig. 2. The absorption  
169 values range from 5.28% to 14.09% for type A samples and from 7.24% to 13.94% for type  
170 B samples. The mean value of water absorption is  $9.58\% \pm 0.51\%$ . The result of the mean  
171 value is presented as a sum of mean values and standard error of the mean of the specified  
172 range. All water absorption results indicate poor concrete quality according to the  
173 International Federation for Structural Concrete (FIB) report (CEB-FIP 1989). The FIB  
174 report (CEB-FIP 1989) categorized concrete quality as poor when water absorption values  
175 are greater than 5%, average quality for 3 to 5% and good quality for 0 to 3% water  
176 absorption. On the other hand, according to the PN-88/B-06250 standard (PN 1988), the

177 water absorption of concrete should not be greater than 5% in the case of concrete exposed  
178 to atmospheric conditions.

179 The dry density values ranged from 1753 to 2119 kg/m<sup>3</sup> for type A samples and from  
180 1788 to 2105 kg/m<sup>3</sup> for type B samples. The obtained values of water absorption are directly  
181 connected with the specified values of dry density. While the dry density values are  
182 increasing, the water absorption values are strongly decreasing. According to the EN 206  
183 (CEN 2013) standard, the concrete can be categorized into three main density grades:  
184 lightweight concrete with dry density from 800 to 2000 kg/m<sup>3</sup>, normal concrete with dry  
185 density from 2000 to 2600 kg/m<sup>3</sup> and heavy concrete with dry density over 2600 kg/m<sup>3</sup>. Only  
186 24% of specimens can be classified as normal concrete with dry density over 2000 kg/m<sup>3</sup>  
187 (see Fig. 2). The mean value for all samples of dry density is 1929.2 ± 23.9 kg/m<sup>3</sup>. On the  
188 other hand, the ACI 318-14 standard (ACI 2014) indicates normal weight concrete with a  
189 density between 2160 and 2560 kg/m<sup>3</sup> (135 to 160 lb/ft<sup>3</sup>).

190 The water absorption  $w_a(\rho)$  can be described as a function of dry density  $\rho$ :

$$wa(\rho) = 49.0945 - 0.0205 \cdot \rho, \quad (1)$$

191 where for dry density  $\rho \in (1706 \div 2119 \text{ kg/m}^3)$ . Good compatibility occurs between the test  
192 results and the assumed straight-line approximation function (see Fig. 2). The computed  
193 determination coefficients fulfill the condition  $R^2=0.94$ . It can be concluded that for the  
194 investigated specimens of 70-year-old concrete, the increase of water absorption is connected  
195 with a linear decrease of dry density values specified by Eq. (1).

### 196 *Chemical properties*

197 The chemical laboratory testing program consists mainly of three sets of tests:  
198 measurement of the pH value, determination of water-soluble chloride salts (Cl<sup>-</sup>) and sulfate  
199 ions (SO<sub>4</sub><sup>2-</sup>). The samples of concrete for chemical analysis were taken from the bottom part



200 of core samples (bottom part of continuous footing) after a cut-off of approximately 4-5 cm  
201 cylindrical samples from the exploratory bore holes. Their general concentration, including  
202 the pH of the test samples (series A and B), was tested after dissolving a given amount of the  
203 mass of the crushed concrete in distilled water. After filtration through membrane filters  
204 (MCE type) with a pore size of 45  $\mu\text{m}$ , the obtained filtrates were tested according to the  
205 standards. The pH was measured according to ISO 10523 (ISO 2008). The extract with  
206 chloride ions was analyzed in accordance with the Volhard method described in EN 1744-  
207 1+A1 (CEN 2009), while the extract with water-soluble sulfate ions was analyzed according  
208 to EN 1744-1+A1 (CEN 2009).

209 The pH value is one of the most useful factors for specifying the ability of concrete to  
210 protect steel rebar. The pH values range from 11.0 to 13.3, while the mean value is equal to  
211  $12.4 \pm 0.1$  (see Fig. 3 and Table 2). It can be seen that only three measurements (14%) are  
212 below the value of 12. The mean pH value is approximately similar to freshly made concrete,  
213 which may vary in the range of 12.5-13.5 (see, e.g., Duffó et al. 2009). As carbonation  
214 proceeds, the pH value of the concrete pore solution decreases. When the pH value decreases  
215 below 9.5, corrosion of the reinforcing steel rebars may be observed.

216 The alkaline reaction of concrete protects the reinforcing steel against corrosion.  
217 Acidifying substances in the environment that cause the neutralization of concrete include  
218 chloride and soluble sulfate. The water-soluble chloride salts and sulfate ions in Tables 3 and  
219 4 are specified as a percentage of cement weight. The chloride content of a concrete expressed  
220 as the percentage of chloride ions by mass of cement shall not exceed the 0.2% limit for  
221 concrete containing steel reinforcement according to standard EN 206 (CEN 2013).  
222 Following the ACI 318 standard (ACI 1989) for reinforced concrete that will be exposed to  
223 chlorides or will be damp in service, the limits are 0.15% and 0.30%, respectively. On the  
224 other hand, an excessive amount of sulfate, derived from aggregates or other constituents in  
225 concrete, can cause disruption due to expansion (see, e.g., Concrete Society 2014). The



226 standard BS 8110-1 1985 edition (BSI 1985) had a limit of 4% by mass of cement based on  
227 the total acid soluble sulfate method expressed as SO<sub>3</sub> (conversion of sulfate SO<sub>4</sub> to SO<sub>3</sub> may  
228 be assumed as 0.833 x SO<sub>4</sub> = SO<sub>3</sub>). This restriction was abandoned in the standard BS 8110-  
229 1 1997 edition (BSI 1997).

230 The water-soluble chloride salt values range from 0.015% to 0.23%, and the mean value  
231 is 0.067% ± 0.011% (see Fig. 4 and 5). One of the concrete specimens was identified with a  
232 value over the 0.2% limit of cement weight specified by standard EN 206 (CEN 2013). When  
233 the chloride content in concrete is close to the 0.2-0.3% of cement weight, it can be concluded  
234 that the concrete is being exposed to chloride attack.

235 The sulfate ion (SO<sub>4</sub><sup>2-</sup>) values range from 0.035% to 0.30%, and the mean value is equal  
236 to 0.094% ± 0.015% (see Fig. 4 and 5). The low concentration of sulfates ions in concrete  
237 samples indicates that the low contamination is due to external sources (e.g., groundwater).  
238 When high values of water-soluble chloride salts and sulfate ions are observed in concrete  
239 located in the ground environment, examining the soil properties should be taken into  
240 consideration.

#### 241 *Mechanical tests*

242 The uniaxial experimental tests used the Advantest 9 C300KN mechanical testing  
243 apparatus, as shown in Fig. 6. The experiments were performed to failure of the concrete  
244 cylinder specimens and used a constant rate of loading with the range of 0.6 MPa/s according  
245 to EN 12390-3 (CEN 2001a). The compressive strength was calculated using the following  
246 equation:

$$f_c = \frac{F}{A_c}, \quad (2)$$

247 where  $f_c$  is the compressive strength,  $F$  is the maximum load at failure, and  $A_c$  is the cross-  
248 sectional area of the specimen.



249 Uniaxial tensile test results of compressive strength versus dry density are presented in  
250 Fig. 7. The compressive strength of cylinder specimens ranges from 6.9 MPa to 29.3 MPa  
251 for type A samples and from 5.9 MPa to 37.3 MPa for type B samples. The mean values of  
252 compressive strength are  $19.05 \pm 2.45$  MPa for type A and  $25.08 \pm 3.29$  MPa for type B  
253 samples. Taking into account the mean values of compressive strength, it can be seen that the  
254 concrete can be classified to compressive strength class C20/25 (cylinder/cube) according to  
255 standard EN 206 (CEN 2013) and fulfils the minimum requirements for compressive strength  
256 for structural concrete (min.  $f_c = 17.24$  MPa (2500 psi)) indicated by standard ACI 318-14  
257 (ACI 2014).

258 A wide scatter of compressive strengths due to variations in density properties can be  
259 observed. For a dry density values over  $1920 \text{ kg/m}^3$ , all values of compressive strength are  
260 over 20 MPa. Additionally, the mean value of compressive strength for normal concrete type  
261 (specimens with density above  $2000 \text{ kg/m}^3$ ) is  $27.96 \pm 2.45$  MPa.

262 Additionally, a wide scatter in compressive strength may depend on the types of  
263 aggregate used to prepare the old concrete mix. Some concrete cores exhibited coarse  
264 aggregates (large stones, see Fig. 8) with cavities and pores. It should be noted that the  
265 measured compressive strength of a core will generally be lower than that of a corresponding  
266 properly melded and cured standard cylinder tested at the same age.

### 267 *Modulus of elasticity*

268 The determination of the modulus of elasticity for diamond-drilled concrete cores of type  
269 A (cylinders having the length to diameter ratio  $L/D=2$ ) was specified according to guidelines  
270 given by the ASTM C469M standard (ASTM 2014). The cylindrical specimens were stored  
271 and tested at room temperature (approximately  $20^\circ\text{C}$ ) in air-dry conditions. It should be noted  
272 that only cores with a length-to-diameter ratio greater than 1.50 may be used in a  
273 compressometer device for measuring the static modulus of elasticity. The modulus of

274 elasticity of the concrete corresponds to the average slope of the stress-strain responses  
275 captured during cyclic loading. The modulus of elasticity  $E_{0.0-0.4}$  in an applicable customary  
276 working stress range from 0 to 40% of the ultimate concrete strength was specified.  
277 Additionally, the modulus of elasticity  $E_{0.1-0.3}$  ranging from 10% to 30% of ultimate concrete  
278 strength was determined. The value of one-third of the ultimate strength is required in the  
279 ISO 1920-10:2010 standard (ISO 2010). On the other hand, the EN 1992-1-1 (CEN 2004)  
280 standard defines the modulus of elasticity as a secant value between 0% and 40% of the  
281 ultimate strength for concrete with quartzite aggregates, and for limestone and sandstone  
282 aggregates, the value should be reduced by 10% and 30%, respectively. The ASTM C469M  
283 standard (ASTM 2014) also indicates a 40% ultimate load to calculate the modulus of  
284 elasticity.

285 The modulus of elasticity ranges from 6890 MPa to 19030 MPa for  $E_{0.0-0.4}$  and from 6890  
286 MPa to 19450 MPa for  $E_{0.1-0.3}$  (see Fig. 9). The differences between the  $E_{0.0-0.4}$  and  $E_{0.1-0.3}$   
287 values are small (0-7%). The mean values of the modulus of elasticity are  $12560 \pm 1200$  MPa  
288 for  $E_{0.0-0.4}$  and  $12630 \pm 1240$  MPa for  $E_{0.1-0.3}$ . The obtained result can be bisectonal (see Fig.  
289 9) as below and over 20 MPa of the compressive strength (it corresponds to a dry density  
290 below and over  $1920 \text{ kg/m}^3$ , respectively). When compressive strength values are increased,  
291 the modulus of elasticity values substantially increase.

## 292 **Discussion and Conclusions**

293 The main objective of the present investigation was to assess the state of 70-year-old  
294 concrete built in the continuous footing of an office building. On the basis of the selected  
295 mechanical, physical and chemical properties, the following conclusions may be drawn:

- 296 • The water absorption of concrete specimens ranging from approximately 5% to 14%  
297 indicates poor concrete quality.

- 298 ● The dry density of concrete cores ranged from approximately 1750 kg/m<sup>3</sup> to 2100  
299 kg/m<sup>3</sup>. Most concrete specimens were classified as lightened concrete, while only  
300 24% of specimens were normal concrete (according to the EN 206 (CEN 2013)) with  
301 a dry density over 2000 kg/m<sup>3</sup>.
- 302 ● The pH values indicate that corrosion of the reinforcing steel rebars should not be  
303 observed. Nevertheless, the steel rebar corrosion was detected by visual inspection in  
304 two core samples in a place where a very low concrete cover was measured.  
305 Generally, all reinforcements with proper concrete cover were in good condition  
306 without any corrosion center. The specified values of water-soluble chloride salts and  
307 sulfate ions showed that the investigated concrete was not exposed to chloride attack  
308 with a low concentration of sulfates ions.
- 309 ● The cylindrical compressive strength (for type A specimens) ranged from 6.9 MPa to  
310 29.3 MPa (with a mean value equal to  $19.05 \pm 2.45$  MPa) and cube compressive  
311 strength (for type B specimens) ranged from 5.9 MPa to 37.3 MPa (with a mean value  
312 equal to  $25.08 \pm 3.29$  MPa). The wide scatter of compressive strength with the  
313 modulus of elasticity, ranging from 6890 MPa to 19030 MPa for  $E_{0.0-0.4}$ , indicated  
314 poor concrete quality.
- 315 ● The 70-year-old concrete had a high scatter of chemical and mechanical properties.  
316 The wide scatter in density, water absorption, compressive strength and modulus of  
317 elasticity resulted in a very low quality control during construction. The poor quality  
318 of old concrete can be explained by production technology, which was probably based  
319 on portable concrete mixers with handmade proportions of concrete components.  
320 Additionally, a lack of uniform compaction during the placement of mix concrete was  
321 observed during core drilling. It may be pointed out that the 1<sup>st</sup> reinforced concrete  
322 code (NACU 1910) indicates that *reinforced concrete may be used in accordance*  
323 *with good engineering practice*, but sometimes, old structures are poor quality.



324 Concrete and reinforced concrete structures require proper operational use and  
325 appropriate protection from environmental conditions. Several existing reinforced concrete  
326 buildings, bridges and viaducts reached a critical state of degradation, and evaluation of their  
327 durability and mechanical properties is indispensable. Construction and building inspection  
328 should indicate a critical state of structure element degradation. Expert opinion of old  
329 concrete construction should be accompanied by in situ inspection and testing of concrete  
330 specimens taken directly from construction elements. A general evaluation of the mechanical  
331 properties of old concrete is not inefficient. In several cases, it is necessary to incorporate  
332 scientific and engineering communities to evaluate the performance of old structures. The  
333 authors are hopeful that the described investigation sparks interest a wide group of engineers  
334 and scientists to take into consideration the subject of old concrete structures.

335

336 **References**

337 ACI (American Concrete Institute). (1989). “Building code requirement for reinforced  
338 concrete.” *ACI 318-89*, Farmington Hills, MI.

339 ACI (American Concrete Institute). (2014). “Building Code Requirements for Structural  
340 Concrete.” *ACI 318-14*, Farmington Hills, MI. ASTM International (American Society for  
341 Testing and Materials). (2013). “Standard Test Method for Measurement of Rate of  
342 Absorption of Water by Hydraulic-Cement Concretes .” *ASTM C1585 – 13*, West  
343 Conshohocken, PA

344 ASTM International (American Society for Testing and Materials). (2014). “Standard Test  
345 Method for Static Modulus of Elasticity and Poisson’s Ratio of Concrete in Compression.”  
346 *ASTM C469M – 14*, West Conshohocken, PA

347 ASTM International (American Society for Testing and Materials). (2015). “Standard Test  
348 Method for Slump of Hydraulic-Cement Concrete.” *ASTM C143/C143M – 14a*, West  
349 Conshohocken, PA

350 ASTM International (American Society for Testing and Materials). (2018). “Standard  
351 Practice for Making and Curing Concrete Test Specimens in the Field.” *ASTM C31/C31M*  
352 – 18b, West Conshohocken, PA

353 Blanco, A., Segura, I., Cavalaro, SHP., Chinchon-Paya, S., and Aguado, A. (2016). “Sand-  
354 Cement concrete in the century-old Camarasa Dam.” *J. Perform. Constr. Facil.*,  
355 10.1061/(ASCE)CF.1943-5509.0000823, 04015083.

356 BSI (British Standards Institution). (1985). “Structural use of concrete – Part 1: Code of  
357 practice for design and construction.” *BS 8110-1*, UK.

358 BSI (British Standards Institution). (1997). “Structural use of concrete – Part 1: Code of  
359 practice for design and construction.” *BS 8110-1*, UK.

360 CEB-FIP (Euro-International Committee for Concrete-International Federation for Pre-  
361 stressing). (1989). "Diagnosis and Assessment of Concrete Structures - State-of-Art." Report  
362 No. 192.

363 CEN (European Committee for Standardization). (2001a). "Test hardening concrete – Part 3:  
364 Compressive strength of test specimens." *EN 12390-3*, Brussels, Belgium.

365 CEN (European Committee for Standardization). (2001b). "Common rules for precast  
366 concrete products." *EN 13369*, Brussels, Belgium.

367 CEN (European Committee for Standardization). (2004). "Eurocode 2: Design of concrete  
368 structures - Part 1-1: General rules and rules for buildings." *EN 1992-1-1*, Brussels, Belgium.

369 CEN (European Committee for Standardization). (2009). "Testing concrete in structures -  
370 Part 1: Cored specimens - Taking, examining and testing in compression." *EN 12504-1*,  
371 Brussels, Belgium.

372 CEN (European Committee for Standardization). (2009). Tests for chemical properties of  
373 aggregates. Part 1: Chemical analysis." *EN 1744-1+A1*, Brussels, Belgium.

374 CEN (European Committee for Standardization). (2013). "Concrete -- Specification,  
375 performance, production and conformity." *EN 206+A1*, Brussels, Belgium.

376 Concrete Society. (2014). "Analysis of hardened concrete A guide to tests, procedures and  
377 interpretation of results." Technical Report 32 2nd Edition, UK.

378 Dawczynski, S., Brol, J. (2016). "Laboratory tests of old reinforced concrete precast bridge  
379 beams." *Architecture Civil Engineering Environmental*, 9(2), 57-63.

380 De Schutter, G., and Audenaert, K. (2004). "Evaluation of water absorption of concrete as a  
381 measure for resistance against carbonation and chloride migration." *Materials and*  
382 *Structures*, 37, 591.

383 Duffó G.S., Farina S.B., and Giordano C.M. (2009). "Characterization of solid embeddable  
384 reference electrodes for corrosion monitoring in reinforced concrete structures."  
385 *Electrochimica Acta*, 54(1), 1010-1020.





386 Gibas, K., Glinicki, M.A., Józwiak-Niedźwiecka, D., Dąbrowski, M., Nowowiejski, G., and  
387 Gryziński, M. (2015). “Properties of the thirty years old concrete in unfinished Żarnowiec  
388 Nuclear Power Plant.” *Procedia Engineering*, 108, 124-130.

389 ISO (International Organization for Standardization). (2008). “Water quality – Determination  
390 of pH.” *ISO 10523*, Geneva, Switzerland.

391 ISO (International Organization for Standardization). (2010) “Testing of concrete — Part 10:  
392 Determination of static modulus of elasticity in compression.” *ISO 1920-10*, Geneva,  
393 Switzerland.

394 Kelham, S. (1988). “A water absorption test for concrete.” *Magazine of Concrete Research*,  
395 40(143), 106-110.

396 Ma, H. (2014). “Mercury intrusion porosimetry in concrete technology: tips in measurement,  
397 pore structure acquisition and application.” *J Porous Mater*, 21, 207-215.

398 Muntean, M., Noica, N., Radu, L., Ropota, I., Ionescu, A., and Muntean, O. (2008).  
399 “Concrete carbonation and its durability.” *Revista Romania de Materiale-Romanian Journal*  
400 *of Materials*, 38, 284-292.

401 NACU (National Association of Cement Users). (1910). “Standard Building Regulations for  
402 the Use of Reinforced Concrete.” *Standard No. 4*, Philadelphia, PA

403 Pettigrew, Ch.S., Barr, P.J., Maguire, M., and Halling, M.W. (2016). “Behavior of 48-Year-  
404 Old Double-Tee Bridge Girders Made with Lightweight Concrete” *Journal of Bridge*  
405 *Engineering*, 10.1061/(ASCE)BE.1943-5592.0000921, 0000921.

406 PKN (Polish Committee for Standardization). (1945). “Concrete and reinforced concrete  
407 structures. Structural analysis and design (in Polish).” *PN-B-195*, Warsaw, Poland.

408 PKN (Polish Committee for Standardization). (1988). “Normal concrete. (in Polish)” *PN-*  
409 *88/B-06250*, Warsaw, Poland.

410 Qazweeni, J., and Daoud, O. (1991). “Concrete deterioration in a 20-years-old structure in  
411 Kuwait.” *Cement and Concrete Research*, 21(6), 1155-1164.



- 412 Sena-Cruz, J., Ferreira, R.M., Ramos, L.F., Fernandes, F., Miranda, T., and Castro, F. (2013).  
413 “Luiz Bandeira Bridge: Assessment of a Historical Reinforced Concrete (RC) Bridge.”  
414 *International Journal of Architectural Heritage*, 7(6), 628-652.
- 415 Šimonová, H., Daněka, P., Frantíka, P., Keršnera, Z., and Veselýa, V. (2017). “Tentative  
416 Characterization of Old Structural Concrete through Mechanical Fracture Parameters.”  
417 *Procedia Engineering*, 190, 414-418.

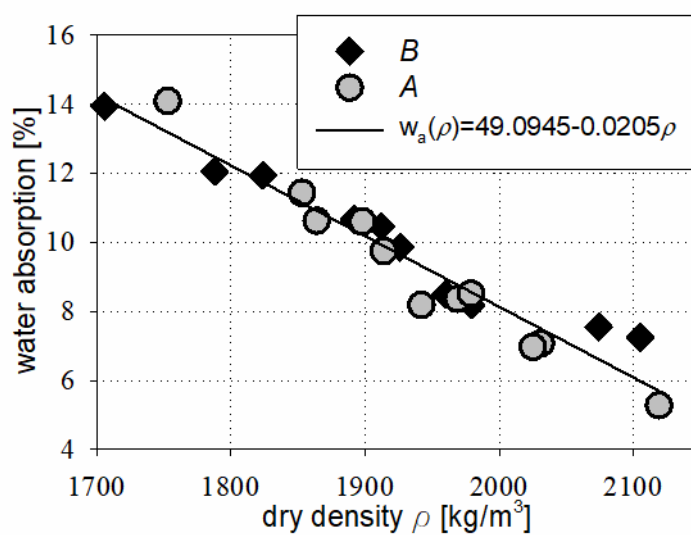




296

297

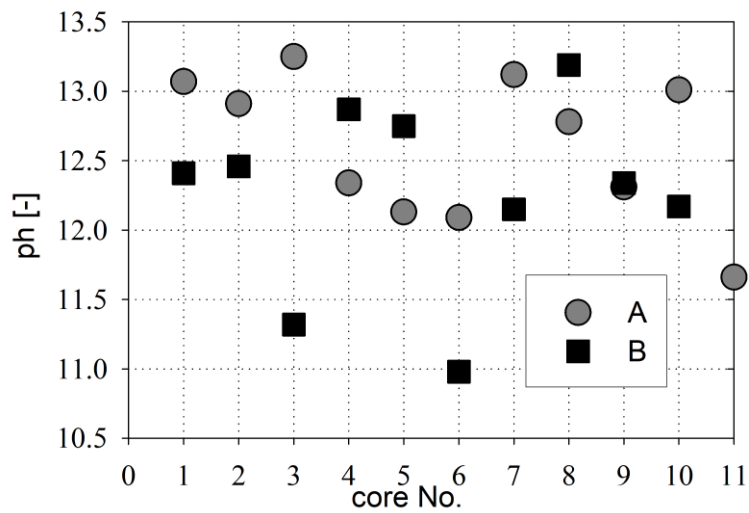
Figure 1. Core samples type A and B after cut geometry preparation



298

299

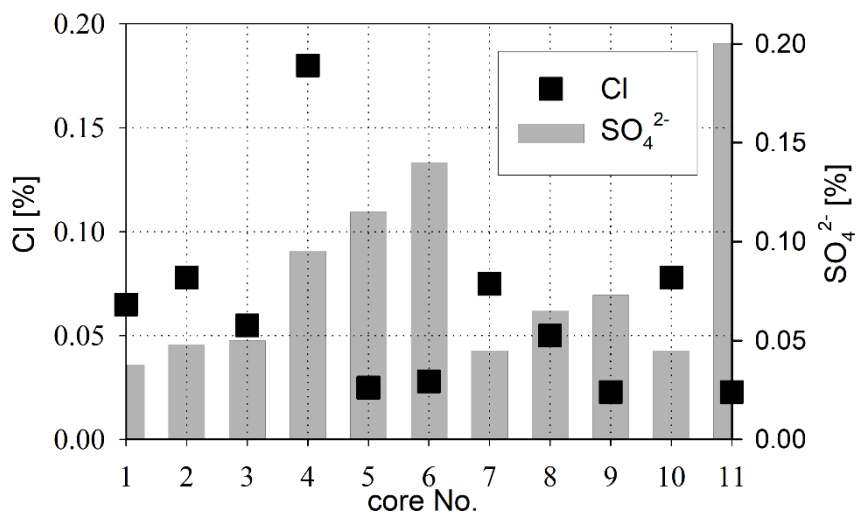
Figure 2. Water absorption versus dry density



300

301

Figure 3. pH values of concrete specimens



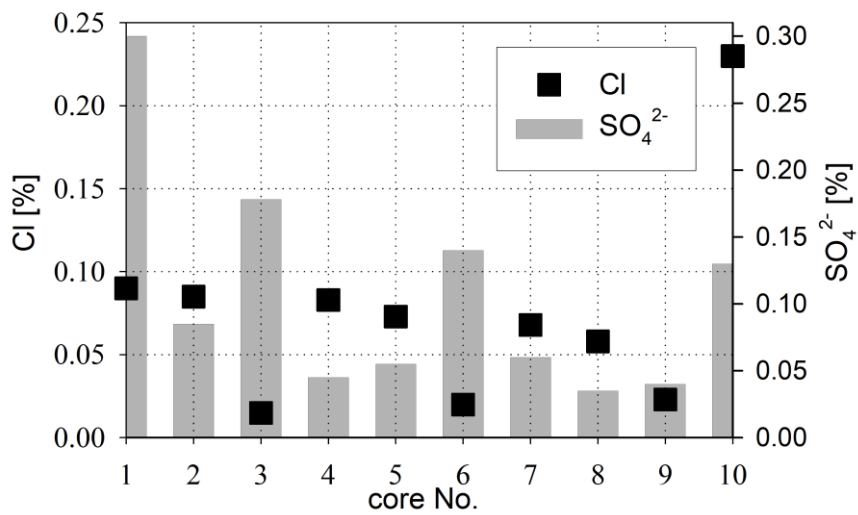
302

303

Figure 4. Chloride and soluble sulphate content as a percent of cement weight for A type

304

specimens



305

306

Figure 5. Chloride and soluble sulphate content as a percent of cement weight for B type

307

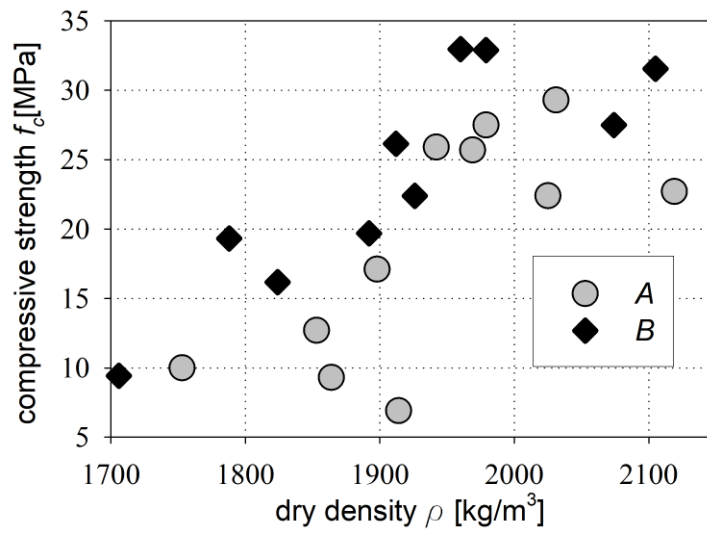
specimens



308

309

Figure 6. Laboratory test stand



310

311

Figure 7. Compressive strength versus dry density for core samples type A and B





312

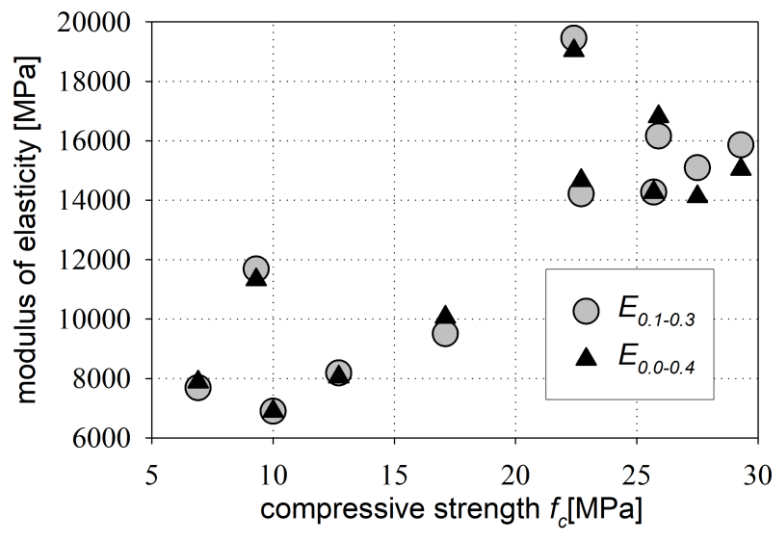


313

314

Figure 8. Damaged concrete cores with visible coarse aggregate (stone)





315

316 Figure 9. Modulus of elasticity versus compressive strength for diamond-drilled concrete

317

cores type A



287  
288

Table 1. Concrete strength [MPa] ( $[\text{kg}/\text{cm}^2]$ ) depending on the amount of cement in  $1 \text{ m}^3$  of finished concrete on the degree of liquidity and the ratio of sand to gravel or crushed stone

The amount of cement [kg] in $1 \text{ m}^3$ of concrete mix	Volume ratios					
	sand to gravel 1:1 or sand to stone gravel 1:0.8			sand to gravel 1:2 or sand to stone gravel 1:1.6		
	liquid	plastic	rammed	liquid	plastic	rammed
200	0 (0)	2.94 (30)	5.89 (60)	3.92 (40)	8.83 (90)	11.77 (120)
300	4.90 (50)	8.83 (90)	11.77 (120)	9.81 (100)	13.73 (140)	15.69 (160)
400	9.81 (100)	13.73 (140)	15.69 (160)	13.73 (140)	17.66 (180)	<b><u>19.62 (200)</u></b>

289

**Table 2.** pH values of concrete specimens (series A and B)

<b>Samples</b>	<b>pH</b>	<b>Samples</b>	<b>pH</b>
A1	13.1	B1	12.4
A2	12.9	B2	12.5
A3	13.3	B3	11.3
A4	12.3	B4	12.9
A5	12.1	B5	12.8
A6	12.1	B6	11.0
A7	13.1	B7	12.2
A8	12.8	B8	13.2
A9	12.3	B9	12.3
A10	13.0	B10	12.2
A11	11.7	-	-

**Table 3.** The content of chloride ions (Cl<sup>-</sup>) in concrete as a percent of cement weight

<b>Samples</b>	<b>Cl [%]</b>	<b>Samples</b>	<b>Cl [%]</b>
A1	0.065	B1	0.090
A2	0.078	B2	0.085
A3	0.055	B3	0.015
A4	0.180	B4	0.083
A5	0.025	B5	0.073
A6	0.028	B6	0.020
A7	0.075	B7	0.068
A8	0.050	B8	0.058
A9	0.023	B9	0.023
A10	0.078	B10	0.230
A11	0.023	-	-

**Table 4.** The content of sulphate ions ( $\text{SO}_4^{2-}$ ) in concrete as a percent of cement weight

<b>Samples</b>	<b><math>\text{SO}_4^{2-}</math> [%]</b>	<b>Samples</b>	<b><math>\text{SO}_4^{2-}</math> [%]</b>
A1	0.038	B1	0.300
A2	0.048	B2	0.085
A3	0.050	B3	0.178
A4	0.095	B4	0.045
A5	0.115	B5	0.055
A6	0.140	B6	0.140
A7	0.045	B7	0.060
A8	0.065	B8	0.035
A9	0.073	B9	0.040
A10	0.045	B10	0.130
A11	0.200	-	-