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Chemical and mechanical properties of 70-year-old concrete

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

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

Introduction

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

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

The preservation and protection of old buildings require necessary information about their main structure durability to ensure safe operational use by inhabitants or other people. A proper assessment of the mechanical properties of old concrete using laboratory tests strongly impacts the level of precision in an expert opinion or economical design. The investigation of old concrete structures has been considered not only by engineers but also by scientists. Qazweeni and Daoud 1991 examined the physical, mechanical and chemical properties of concrete core specimens taken from a 20-year-old office building. The authors concluded that the used concrete had low density, high absorption ratios and voids. Furthermore, the observed failure of the concrete structure was caused by chloride and carbonation attacks. Muntean et al. 2008 investigated the mechanical properties of old concrete constructions that underwent the carbonation process. The main conclusion was that the increased content of belite in the Portland cement had a positive influence on concrete durability, particularly upon the rate of carbonation. Sena-Cruz et al. 2013 studied the mechanical and chemical properties of structural materials of a reinforced concrete bridge built in 1907. Laboratory tests showed a high porosity in the concrete (7-10%); nevertheless, a concrete strength class greater than C30/37 and average modulus of elasticity (approximately 30 GPa) were determined. Gibas et al. 2015 examined the compressive strength of cored concrete specimens, chloride penetration and the rate of water absorption of an unfinished concrete structure of a nuclear power plant, which was exposed for over 30 years to environmental conditions. The authors noted that the compressive strength was above 60 MPa with low carbonation depth; however, the rate of water absorption and the coefficient of chloride migration showed a large dispersion of concrete quality. Blanco et al. 2016 examined the chemical reactions leading to the degradation of a 95-year-old concrete dam manufactured with sand-cement as a binder. The results revealed that the concrete in the main dam body exhibited satisfactory mechanical properties with a pH of over 10 despite the degradation of approximately 15 cm of the superficial dam layer. Dawczynski and Brol 2016 performed mechanical and chemical laboratory tests for 40-year-old reinforced concrete precast bridge beams. Šimonová et al. 2017 performed three-point bending fracture tests on structural concrete from a 1970s railway station and determined the modulus of elasticity, fracture toughness, toughness and fracture energy. Pettigrew et al. 2016 performed laboratory testing of nearly 50-year-old concrete bridge girders to specify the effective prestress, flexural capacity, and deck punching shear strength.

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

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

Materials and Design

The proposed research addresses experiments performed to determine the selected mechanical, physical and chemical properties of 70-year-old concrete core samples. The cylindrical specimens were taken from the continuous footing of an office building by a concrete core bore hole diamond drill machine (see Fig. 1) from locations with similar geometrical and boundary conditions. The thickness of the continuous footing was approximately 70 cm, and the top surface was at an elevation of +13.2 masl (meters above sea level). The altitude under the surrounding ground level was (+14.0 to 14.15 masl). The office building was built in the early 1950s in Gdansk, Poland. The structural analysis was carried out by Prof. W. Bogucki in March 1948.

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

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

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

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

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

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

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

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

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

Laboratory tests

Tests of water absorption

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

The water absorption results versus dry density are presented in Fig. 2. The absorption values range from 5.28% to 14.09% for type A samples and from 7.24% to 13.94% for type B samples. The mean value of water absorption is 9.58% ± 0.51%. The result of the mean value is presented as a sum of mean values and standard error of the mean of the specified range. All water absorption results indicate poor concrete quality according to the International Federation for Structural Concrete (FIB) report (CEB-FIP 1989). The FIB report (CEB-FIP 1989) categorized concrete quality as poor when water absorption values are greater than 5%, average quality for 3 to 5% and good quality for 0 to 3% water absorption. On the other hand, according to the PN-88/B-06250 standard (PKN 1988), the water absorption of concrete should not be greater than 5% in the case of concrete exposed to atmospheric conditions.

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

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

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

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

Chemical properties

The chemical laboratory testing program consists mainly of three sets of tests: measurement of the pH value, determination of water-soluble chloride salts (Cl^-) and sulfate ions (SO_4^{2-}). The samples of concrete for chemical analysis were taken from the bottom part of core samples (bottom part of continuous footing) after a cut-off of approximately 4-5 cm cylindrical samples from the exploratory bore holes. Their general concentration, including the pH of the test samples (series A and B), was tested after dissolving a given amount of the mass of the crushed concrete in distilled water. After filtration through membrane filters (MCE type) with a pore size of 45 μm, the obtained filtrates were tested according to the standards. The pH was measured according to ISO 10523 (ISO 2008). The extract with chloride ions was analyzed in accordance with the Volhard method described in EN 1744-1+A1 (CEN 2009), while the extract with water-soluble sulfate ions was analyzed according to EN 1744-1+A1 (CEN 2009).

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

The alkaline reaction of concrete protects the reinforcing steel against corrosion. Acidifying substances in the environment that cause the neutralization of concrete include chloride and soluble sulfate. The water-soluble chloride salts and sulfate ions in Tables **3** and **4** are specified as a percentage of cement weight. The chloride content of a concrete expressed as the percentage of chloride ions by mass of cement shall not exceed the 0.2% limit for concrete containing steel reinforcement according to standard EN 206 (CEN 2013). Following the ACI 318 standard (ACI 1989) for reinforced concrete that will be exposed to chlorides or will be damp in service, the limits are 0.15% and 0.30%, respectively. On the other hand, an excessive amount of sulfate, derived from aggregates or other constituents in concrete, can cause disruption due to expansion (see, e.g., Concrete Society 2014). The standard BS 8110-1 1985 edition (BSI 1985) had a limit of 4% by mass of cement based on the total acid soluble sulfate method expressed as SO_3 (conversion of sulfate SO_4 to SO_3 may be assumed as 0.833 x $SO_4 = SO_3$). This restriction was abandoned in the standard BS 8110-1 1997 edition (BSI 1997).

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

The sulfate ion (SO_4^{2-}) values range from 0.035% to 0.30%, and the mean value is equal to 0.094%±0.015% (see Fig. 4 and 5). The low concentration of sulfates ions in concrete samples indicates that the low contamination is due to external sources (e.g., groundwater). When high values of water-soluble chloride salts and sulfate ions are observed in concrete located in the ground environment, examining the soil properties should be taken into consideration.

Mechanical tests

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

$$f_c = \frac{F}{A_c}, \tag{2}$$

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

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

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

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

Modulus of elasticity

The determination of the modulus of elasticity for diamond-drilled concrete cores of type A (cylinders having the length to diameter ratio L/D=2) was specified according to guidelines given by the ASTM C469M standard (ASTM 2014). The cylindrical specimens were stored and tested at room temperature (approximately 20°C) in air-dry conditions. It should be noted that only cores with a length-to-diameter ratio greater than 1.50 may be used in a compressometer device for measuring the static modulus of elasticity. The modulus of elasticity of the concrete corresponds to the average slope of the stress-strain responses captured during cyclic loading. The modulus of elasticity $E_{0.0\text{-}0.4}$ in an applicable customary working stress range from 0 to 40% of the ultimate concrete strength was specified. Additionally, the modulus of elasticity $E_{0.1\text{-}0.3}$ ranging from 10% to 30% of ultimate concrete strength was determined. The value of one-third of the ultimate strength is required in the ISO 1920-10:2010 standard (ISO 2010). On the other hand, the EN 1992-1-1 (CEN 2004) standard defines the modulus of elasticity as a secant value between 0% and 40% of the ultimate strength for concrete with quartzite aggregates, and for limestone and sandstone aggregates, the value should be reduced by 10% and 30%, respectively. The ASTM C469M standard (ASTM 2014) also indicates a 40% ultimate load to calculate the modulus of elasticity.

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

Discussion and Conclusions

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

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

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

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

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Figure Legends

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

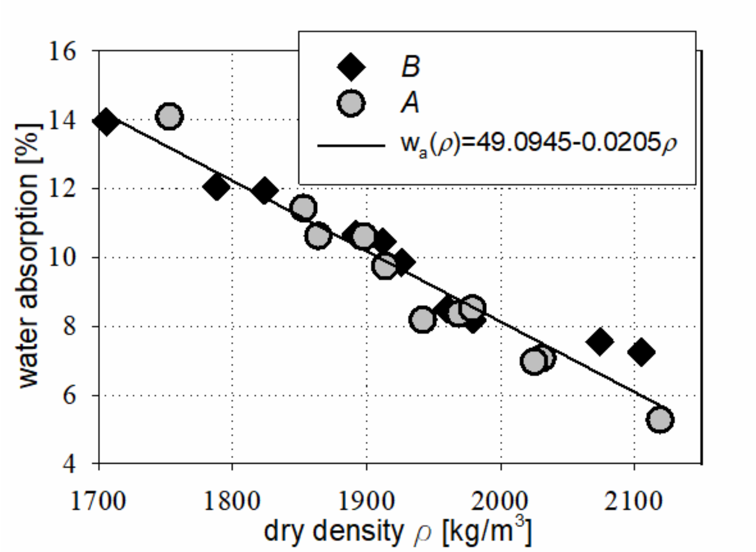

Figure 2. Water absorption versus dray density

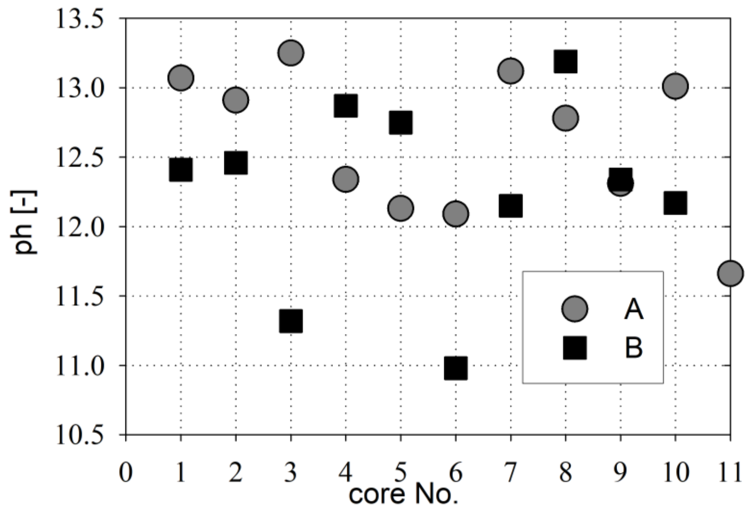

Figure 3. pH values of concrete specimens

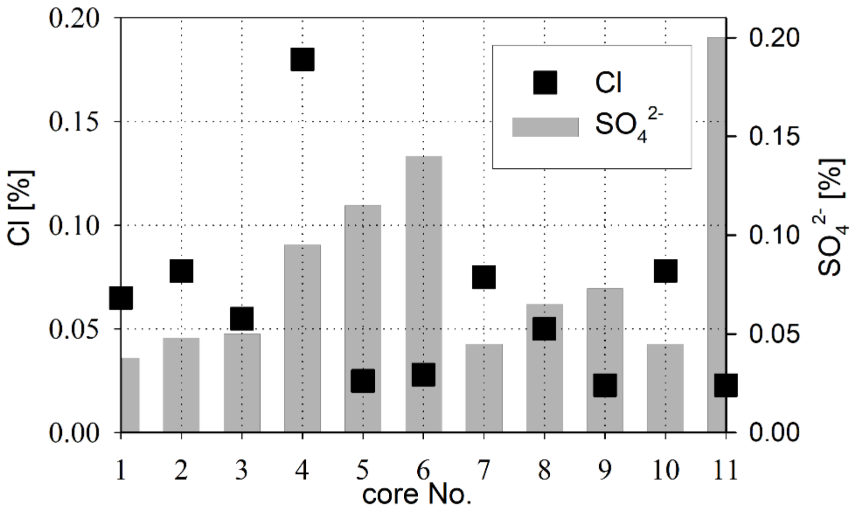

Figure 4. Chloride and soluble sulphate content as a percent of cement weight for A type specimens

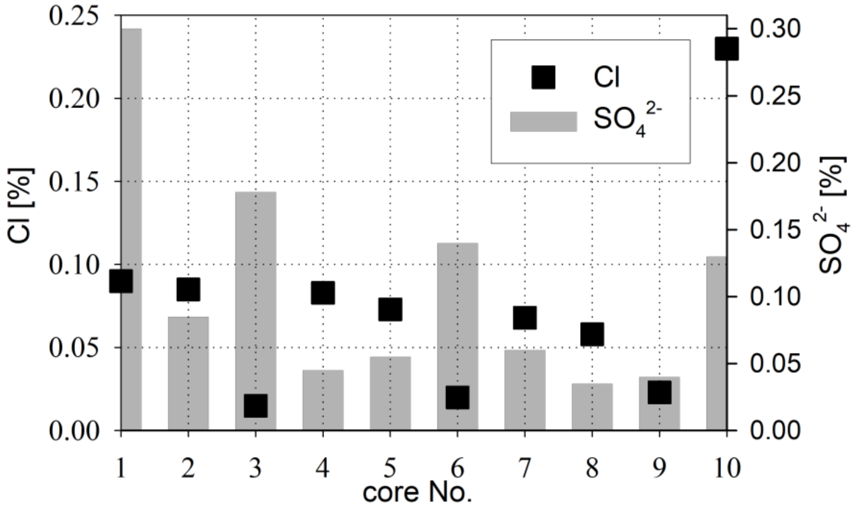

Figure 5. Chloride and soluble sulphate content as a percent of cement weight for B type specimens

Figure 6. Laboratory test stand

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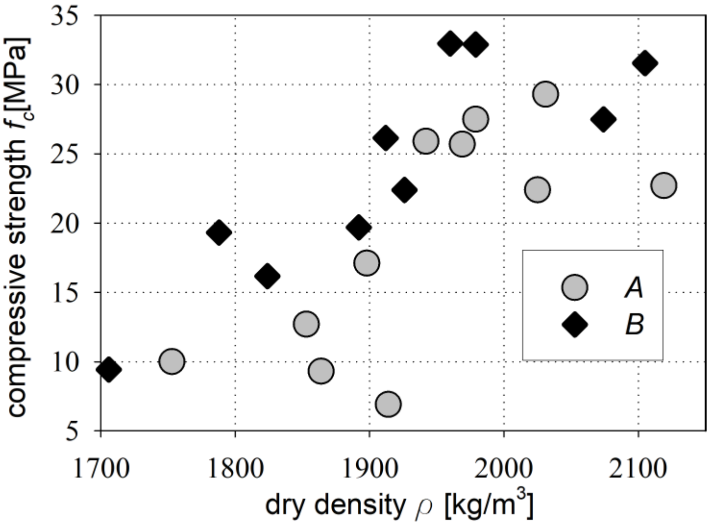

311 Figure 7. Compressive strength versus dray density for core samples type A and B

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

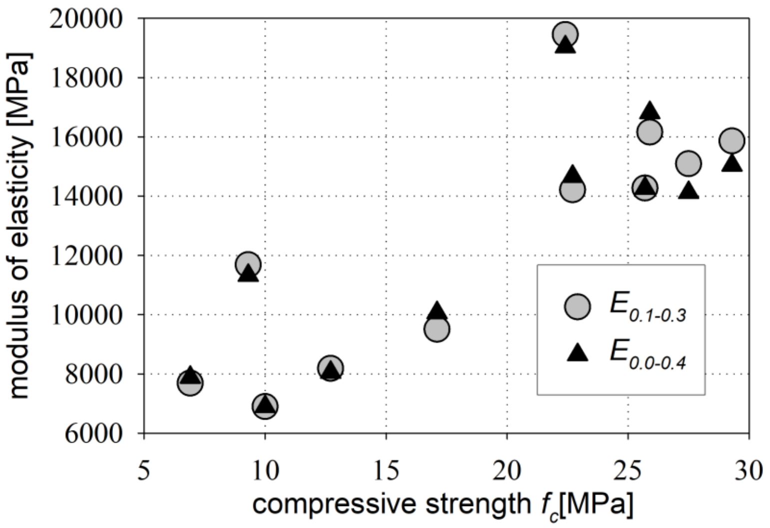

Figure 9. Modulus of elasticity versus compressive strength for diamond-drilled concrete cores type A

Table 1. Concrete strength [MPa] ([kg/cm^2]) depending on the amount of cement in 1 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 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)	**19.62 (200)**

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

Samples	pH	Samples	pH
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^-) in concrete as a percent of cement weight

Samples	Cl [%]	Samples	Cl [%]
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 (SO_4^{2-}) in concrete as a percent of cement weight

Samples	**SO_4^{2-} [%]**	**Samples**	**SO_4^{2} [%]**
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	-	-