CHARACTERIZATION STUDIES ON CEMENT CONGLOMERATES FROM HISTORIC REINFORCED CONCRETE STRUCTURES

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Abstract

Reinforced cement conglomerate underwent considerable development and use since its invention. Yet, the mechanical properties and resistance to deterioration have not always matched expectations, as observed in several historical structures. This is mainly due to the difficulty in obtaining a constantly high quality material, because of heterogeneity of constituents, poor productive technology and lack of adequate mix design.

The purpose of this research is to carry out a full characterization of different concrete samples extracted from historical structures, by means of petrographic studies, image analysis techniques, XRPD, SEM, μCT, elemental chemical analysis and computer simulations. The study is aimed at determining not only the characteristics of the materials’ components, their relative proportions and textural features, but also the nature of the alteration phenomena occurred, to relate the structural and mechanical behaviour of the conglomerates to their compositional and microstructural nature and finally to indicate proper restorations protocols and materials.

1. Introduction

Patented by Joseph Monier in 1867, the reinforced concrete became a highly successful material during the 20th century, capable of satisfying the most challenging demands of designers and engineers. However, even though its introduction in construction paved the way for a century of continuous technological innovation in the building industry, the mechanical behaviour of structures made with this material was not fully understood for a long time, giving rise to a variety of structural problems of the buildings built in the first decades of the 20th century. The basic problem was not only the empirical conception of the structural calculations, but also the lack of development of standard concrete production technology and the poor attention paid to the choice of raw materials and their mixing methodology. Furthermore, the problem of reinforced concrete behaviour to external chemical-physical degrading agents was not considered during most of the 20th century, due to the wrong assumption of “infinite durability” of this material.

Given the complexity of the material, a combined multidisciplinary approach, covering the engineering and material science fields, is necessary to obtain a full mechanical and microstructural characterization of reinforced concrete structures and, consequently, to plan and perform proper interventions with adequate restoration materials for the rehabilitation and structural improvement of this modern heritage.

2. Research aims and methods

The main aim of this research project is to carry out a full petrographic, mineralogical and microstructural characterization of cement conglomerates from historic reinforced concrete structures differing in age and destination of use, as well as to correlate the material characteristics with their mechanical properties, resulting from mechanical tests on samples taken in-situ.

In detail, the research is articulated in three phases, each one characterized by specific study methodologies:

- Typological and quantitative characterization of material components: aggregate, cement matrix, interfacial transition zone, pore network. The typological characterization, especially regarding mineralogy and petrography of the aggregate at different grain sizes, will be determined by means of petrographic examination following the ASTM C 856-04 standard. Abundance of specific components and relative ratios – especially cement abundance, water/cement and cement/aggregate ratios – will be determined by means of multiscale image analysis techniques. A possible approach is the combination of a macroscale analysis based on digitalised images of polished slabs obtained on a flatbed scanner (Linares et al., 2009), and a microscale analysis made by combining BSE images and
elemental maps of concrete thick sections under SEM (Stutzman, 2004). Data should be then confirmed crosschecking with results obtained through other analytical techniques, such as mercury intrusion porosimetry (Kumar & Bhattacharjee, 2004), 3D image analysis on μCT reconstructions (Wong & Chau, 2005), and determination of total cement content of concrete following the ASTM C 1084-02 standard;

- Study of the chemical and physical alteration, and its dynamics, by means of a multianalytical approach including petrographic examination, XRPD analysis, microstructural and microchemical study at SEM-EDS and elemental chemical analysis by means of atomic absorption spectrophotometry;
- Correlation between material characteristics and compression strength – determined by mechanical tests – by means of multiple linear regression model calculations (Zain & Abd, 2009), and computer modelling with the VCCTL software developed by NIST (Benz et al., 2003).

3. Activities of the first year

During this first year, the activity mainly focused on the individuation of proper case studies. Six building have been chosen so far, differing in age, constructive methodology and destination of use:

- Northern wing of the Carraresi Castle (Padua). Originally built between the 13\textsuperscript{th} and 14\textsuperscript{th} century, the building was heavily modified between the end of the 19\textsuperscript{th} century and the middle of the 20\textsuperscript{th} century, with the construction of several reinforced concrete structural elements;
- Civic Theatre (Schio, Vicenza). The structure was built during the first decade of the 20\textsuperscript{th} century, with a composite masonry-reinforced concrete technique;
- “Ex Tiro a Volo” complex (Venice Lido). The structure was built in 1949, with reinforced concrete structural elements;
- “Ex Ricamificio” (San Giovanni Lupatoto, Verona). Originally built in 1926, the structure was raised in 1964 with the construction of a great hall covered by a reinforced concrete vault. Partially made with prefabricated elements;
- “Ex Agrimont” area, C3 orthophosphoric acid storehouse (Marghera, Venice). The building was constructed in 1969, and is characterized by the presence of structural arches made with prestressed and prefabricated concrete;
- “Ex Foro Boario” (Padua). Built in 1969, the structure is wholly made by modular elements of prestressed and prefabricated reinforced concrete.

Sampling was conducted following the criteria of minimum invasiveness and maximum representativeness. First of all, the structures were studied on their original projects and by means of in-situ inspections, to individuate proper sampling areas. Then, the disposition of the reinforcement bars within the structural elements was studied by means of magnetic scanner inspections, to avoid damages during the extraction of concrete cores. For every sampling area, a large core of 95 mm diameter and one or more microcores of 20 mm diameter were extracted, by means of a water lubricated concrete core drill and a water lubricated hollow tip drill, respectively. Moreover, superficial fragments of concrete and alteration concretions were sampled, by means of local scarification and superficial ablation.

Compression tests on the sampled cores were then performed at the Structural and Transportation Engineering laboratory. Tests displayed a large variability of $f_{ck}$ values in the materials, ranging from 9.9 to 65.3 MPa.

Part of the experimental activity was also dedicated to the individuation of a proper preparation methodology of the concrete polished slabs for the following image analyses. Good results in term of sample quality and single component recognisability were obtained by vacuum impregnating slab surfaces with fluorescent epoxy resin, in order to enhance pore network identification and polishing them with progressively finer abrasive papers, following the methodology proposed by the ASTM C 457-09 standard.

A preliminary petrographic examination on all the materials sampled was also performed. Conglomerate porosity, determined by comparison with visual estimation diagrams, is comprised between 5 and 10% of the total volume, with abundant irregular entrapped air voids due to bleeding
water, indicating wrong W/C ratios. The inert fraction is mainly constituted by rounded natural carbonatic gravels in the coarse fraction, and quartz sand with unimodal distribution centred on the medium sand grain size class in the fine fraction. The materials have very variable grain size distribution, but generally significantly deviate from the minimum void ideal distribution of the Fuller & Thompson theoretical curve. The cement matrix is generally thoroughly carbonated, with clear interfacial transition zones around the inert fraction. Non-hydrated clinker grains tenths of microns in size are also frequently present. They are generally rich in belite, as confirmed by diffractometry on the grain fraction below 63 μm.

Finally, a preliminary study on the alteration processes affecting all the materials sampled was performed. Observations under polarizing microscope have highlighted, besides the incidence of carbonation phenomena, the absence of alkali-aggregate reactions around reactive aggregates. Moreover, diffractometric analysis performed on the fine grain size fraction below 63 μm showed the presence on most of the samples of secondary phases, mainly gypsum and ettringite, indicating a sulphate attack incidence.

More detailed analytical studies were performed on the concrete samples from the “Ex Tiro a Volo” complex entrance porch and the C3 orthophosphoric acid storehouse of the “Ex Agrimont” area. As regards the first case study, considering the severe decay of the structure and the position near the coastline, colorimetric tests with adequate indicators and elemental chemical analysis by means of atomic absorption spectrophotometry were also performed, besides the XRPD and petrographic analysis, in order to measure the total chlorides content within the materials. The results showed total chlorides content of the ppm order of magnitude, excluding the contribute of this form of alteration to the degrade of the structure.

The nature of the alteration of the C3 storehouse, characterised by severe oxidation of the reinforcement bars and deep exfoliation of the conglomerate, was investigated by means of optical and electron microscopy, XRPD and EDS analysis, showing a complex secondary mineral assemblage given by gypsum, ettringite-thaumasite, hydrocalumite, apatite and ardealite (Figure 3.1). The presence of sulphates within the materials can be related to a severe sulphate attack, while hydrocalumite crystallisation is caused by the degrading action of chlorides (Taylor, 2003), which is also responsible for the intense pitting corrosion of the reinforcement bars. Finally, the occurrence of calcium phosphates is related to the reaction between orthophosphoric acid, gypsum and portlandite, which is present in the conglomerate both as alteration phase and as a co-product of calcium silicate hydration.
Figure 3.1: “Ex Agrimont” area, C3 orthophosphoric acid storehouse (Marghera, Venice). Alteration state on a reinforced concrete arch (A), secondary phases mineralogical association (B) and their microstructural nature (C).

References


SUMMARY OF LAST YEAR'S ACTIVITIES

Courses:


Schools, workshops and congresses:

X School on Synchrotron Radiation: Fundamentals, Methods and Applications. Duino (TS), Italy, 7th-18th September 2009.

Posters:


Publications:


Teaching activities:


Field and experimental activities:

In-situ non destructive and medium destructive analyses on reinforced concrete elements from late 19th – first 20th century buildings located in the Veneto region, coupled with adequate sampling by means of core-hole drilling, local scarification and superficial ablation. All the analyses and sampling operations have been performed in collaboration with the Structural and Transportation Engineering Department of the University of Padova.

Petrographic, mineralogical, microstructural and chemical analyses on the concrete samples taken during the field activities by means of polarizing microscope and SEM observations, EDS microanalysis and XRPD and AAS analysis. All the analyses have been performed at the Geosciences Department, University of Padova.

Analytical studies for the conservation state determination of the “Ex Tiro a Volo” complex entrance porch (Lido of Venice) and formulation of an adequate restoration project. The work, committed by the municipality of Venice (Public Buildings Department) and done in collaboration with the Structural and Transportation Engineering Department of the University of Padova, was aimed at the execution of an urgent restoration of the structure.

Archaeometrical studies by means of petrographic, microstructural and mineralogical analyses on ancient mortars from three castle remains of different ages (Cuol di Ciastiel Castle, Late Roman Empire, Pra di Got Castle, Early Middle Age, Sachuidic Castle, XII-XIII Century), located in the High Tagliamento river Valley (Udine, Italy). All the analyses have been performed at the Geosciences Department, University of Padova.

XRPD analysis and compression tests on mortar samples used for the restoration of the Citadel of Acre, Israel. The analyses have been performed at the Geosciences Department, University of Padova, and at the laboratory of the Structural and Transportation Engineering, University of Padova.

Participation to the “Progetto Paganica”, organized by the RELUIS consortium in collaboration with the National Civil Protection Department, in order to perform an urban survey of the city of Paganica, heavily damaged by the 2009 L’Aquila earthquake. The field activities have been performed from the 27th to the 31st July 2009. During the survey activities a series of mortar samples from various buildings of the town have been sampled and they will be studied from a petrographic and mineralogical point of view, in order to correlate state of damage of the buildings and nature and quality of the building materials.

Participation to a pilot project for the restoration of masonry walls from the town of Onna (L’Aquila, Italy), heavily damaged by the 2009 L’Aquila earthquake, by means of injection grouts. The project is now object of study for the degree thesis in Sciences for Cultural Heritage of Chiara Coletti and is done in collaboration with MAPEI and the Structural and Transportation Engineering Department of the University of Padova. A series of mortar samples taken from different building of the town during a survey performed on the 30th August 2009 have been fully characterized from a petrographic, microstructural, mineralogical and mechanical point of view, in order to formulate restoration products fully compatible with the original materials. The following steps of the project consist of a full characterization of the restoration products and a series of in-situ mechanical and ultrasonic tests both on the damaged and restored walls, to check the effectiveness of the restoration.

Sampling of Roman Terra Sigillata potteries found in the city of Adria (Rovigo, Italy), currently studied from an archaeological point of view by the Ph.D. student in Archaeological Sciences Valentina Mantovani. The samples are now object of a series of microstructural, microchemical and minero-petrographic analyses, performed both at the Geosciences Department, University of Padova and at the Chemical Sciences Department, University of Padova, in collaboration with Dr. Lara Maritan, Dr. Luca Nodari and Prof. Umberto Russo, in order to understand the nature of various types of chromatic turnings.