Case Study

Case study on the mineralogical and petrophysical analysis of reinforced concrete slabs of a highway viaduct of the S.G.C. Orte-Ravenna

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Abstract
For the maintenance of the safety and security of people traveling on the road, renovation of the reinforced concrete is necessary, especially for bridge or viaduct slabs. Being able to quantify the degradation of slabs and propose methodologies for its retrofit or maintenance is crucial not only in the mineralogical-engineering field but also for socio-economic implications. In this study, samples of deck slabs of a viaduct from the highway E45 near the locality of Bagno di Romagna (Emilia Romagna, north of Italy) were subjected to a testing program to evaluate mechanical and mineralogical parameters through thermographic analyses, compression, and Ultrasonic Pulse Velocity tests and morphological observation. The analyses allow to better recognize the damage of the reinforced concrete samples and they have shown that the cause of the detachment of the asphalt has mainly a natural origin, due to temperature variations and precipitation, with a secondary cause in the anthropogenic impact. The work aims to understand the relationships between the structure of the aggregates and the characteristics of concrete to understand the development of degradation. This knowledge could be used to prevent future damages to the highways.

Article Highlights

- Concrete slabs analysed provided information about the relation between damage level, mechanical behaviour, size and distribution of aggregates.
- Thermographic analyses were useful to understand how deep the damage was in the slabs and to detect any detachment of the asphalt.
- Compressive tests, through the failure load value, shown that the ultimate strength level decreased due to formation of microcracks.

Keywords Concrete · Aggregates · Damage · Mechanical tests · Mineralogical analysis

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1 Introduction

Since the discovery of reinforced concrete (RC), it has proven to be a material suitable for new needs and new construction forms [1, 2]. In the beginning, it was used only to build large buildings, then it was used to build works of artistic, monumental, and historical importance [3, 4] and large structures such as bridges and motorway viaducts [5–7]. The decisive turning point for the success of this modern material came when it was realized that by providing concrete with a grid of steel bars, the strength characteristics of the concrete were amplified. This discovery was spread out thanks to designers like Coiget, Lambot, Monier, Perret, Le Corbusier, Wright, Maillart, Torroja, Tange, Aalto [3–8].

At the beginning of the new millennium, concrete was the most used construction material; in Italy, more than 19 million tons were produced per year [9]. Nowadays, the reputation of this revolutionary construction material is weakened due to the awareness that reinforced concrete is not an eternal material but undergoes attacks of different nature which alters its resistance characteristics [10–12]. Over the past thirty years, many reinforced concrete bridges all around the world have suffered structural damage; this is the cause of the drop in the consideration of concrete as the leading bridge material. Corrosion of steel reinforcement, alkali-silica reaction, freeze–thaw damage, and sulphate attack are some of the age-related degradation mechanisms for the RC structures, and corrosion of steel has been identified as being the most widespread and predominant mechanism responsible for the deterioration of the RC structures [13, 14]. Bond behaviour of corroded reinforcement has been experimentally studied by many researchers in the past [15, 16]. However, it must be considered that many factors contribute to the degradation of reinforced concrete, including the neglect of designers, builders, and companies that can lead to the production of material of not excellent quality; but the greatest danger is the exposure of concrete to aggressive environments [17, 18].

In the 1950s and 1960s, Italy underwent a construction boom like few other countries in Europe. As the nation's industry grew, so did the country's infrastructure network, as highway bridges and viaducts [19, 20]. Reinforced concrete became the elixir of construction companies, but the material used was not always suitable for the characteristics of durability and mechanical resistance that these constructions needed, and this, together with the corrosion of steel reinforcement, raises questions about the durability of Italy's more than one million bridges built out of reinforced concrete [21, 22]. Italian highway viaducts are generally made up of longitudinal RC beams resting on pillars on which RC slabs are placed in the transverse direction. The RC slabs are provided with internal steel grids, inserted into formworks filled with concrete. At both the base and the roof of the formwork there are 5 cm concrete layers free of steel rebar, which prevent the steel reinforcement from being in direct contact with the air and with atmospheric agents. This could lead to oxidation and degradation of the internal steel structure and therefore to the weakening of the slab. Being able to quantify the degradation of RC slabs and propose methodologies for its retrofit [21] or maintenance is very important not only in the mineralogical-engineering field but also for socio-economic implications. Thousands of kilometres of viaducts and bridges are in poor conditions and it would be very advantageous to find a solution that would cut the costs of replacing the RC slabs [23, 24].

This work aims to define the relationships between the mechanical characteristics and the mineralogical composition of the viaduct's RC slabs [25, 26] in order to better recognize the degradation of the reinforced concrete. Samples of RC deck slabs were collected in a viaduct of the E45 highway, at the Verghereto junction, near the resort of Bagno di Romagna (Emilia Romagna region, north of Italy), which is located in a mountainous area on the Tuscan-Romagna Apennines. The problems related to viaducts are mainly those connected to the degradation of reinforced concrete for different causes: chemical attacks (chlorides, sulphides, salts) [27–29], atmospheric agents (rain, freeze–thaw cycle) [30, 31], and intensive use [32]. In this work, thermographic analyses were carried out on the RC slabs sampled to determine the most degraded areas and the depth of the degradation [33, 34]. The samples, brought to the laboratories of the University of Ferrara in the form of cylindrical specimens, were subjected to compressive strength tests to analyse the resistance of the material and to perform the microscopy analysis for mineralogical characterization [35].

This study also represents a case study providing material to support both research and education through the transferability of this experience and highlighting the essence and core findings of the research.

2 Materials and methods

2.1 Site and sampling description

Samples of RC deck slabs were collected in a viaduct of the E45 highway, at the Verghereto junction, near the resort of Bagno di Romagna (Emilia Romagna region, north of

Italy), which is located in a mountainous area on the Tuscan-Romagna Apennines.

The viaduct called Fornello 1 was built around 1960, and since the bridge was built, maintenance has been carried out only on the road surface, without in-depth investigations.

The viaduct is made up of four longitudinal RC beams (coloured in red in Fig. 1) which support the RC slabs under investigation [36]. The longitudinal beams are connected by orthogonal beams (coloured in green in Fig. 1). The viaduct deck is constituted by a 20 cm thick RC slab with a transversal principal direction (demolished in Fig. 1). The investigated slabs of size 180 × 50 cm^2 were removed from the deck by cutting them in a transversal direction.

A layer of waterproofing material (inside the yellow circle) is applied above the slabs and a layer of asphalt (inside the blue circle) is applied above it. The deterioration of the steel reinforcement required the complete replacement of the slabs, and therefore it was an extremely onerous retrofit work.

Two sequences of slabs were extracted from the viaduct: the first consisting of 12 slabs, the second of 9 ones. Both sequences were taken from the viaduct in the direction of Orte to Ravenna.

2.2 Structural characterization

This work is the result of an integrated study and an interdisciplinary approach between the Department of Physics and Earth Sciences and the Engineering Department of the University of Ferrara. The first dealt with the mineralogical and petrographic characterization of the collected samples to identify the presence of fractures due to a possible difference in heterogeneous clasts; the second dealt with the engineering characterization of the material through thermographic and compressive tests.

Thermographic analyses, compressive mechanical tests, and study of some samples in thin section observed with the transmission optical microscope were carried out on the collected samples.

Thermographic tests were carried out on four slabs (called L1—Fig. 2a, L2—Fig. 2c, L3—Fig. 2e, and L4—Fig. 2g) in the Structural and Geotechnical Engineering Laboratory (LISG) of the University of Bologna. Two 650 W lamps were used for heating the specimens from various distances (Fig. 3). The air temperature and the relative humidity value during these tests are very important physical variables and must be considered in the data analysis phase. During the tests performed on the samples, the air temperature was between 20.5 and 22.4 °C, while the relative humidity had a value between 45 and 47%. An infrared thermal imaging camera (AVIO TVS700 model, Tokyo, Japan) equipped with an uncooled micro-bolometric focal plane array sensor was used to record the images during the heating and cooling phases of the asphalted surfaces of the RC slabs. The cameras were connected directly to a computer. The spectral range of this thermal imaging camera was 8–14 microns; the thermal resolution was 0.08 °C; the infrared optic was 35 mm with a field of view of 26.0° (H) × 19.0° (V) and a geometric resolution of 1.4 mrad. The elaborated images allowed the reconstruction of a continuous sequence that allows verifying the different responses to the thermal excursions of the samples. The processing of thermographic images produced sequences relating to the heating and cooling cycles. Table 1 shown all the steps carried out in the two phases of heating and cooling for all 4 samples analysed.

Concerning the mechanical characterization, cylindrical cores were drilled from the slabs to be subjected to

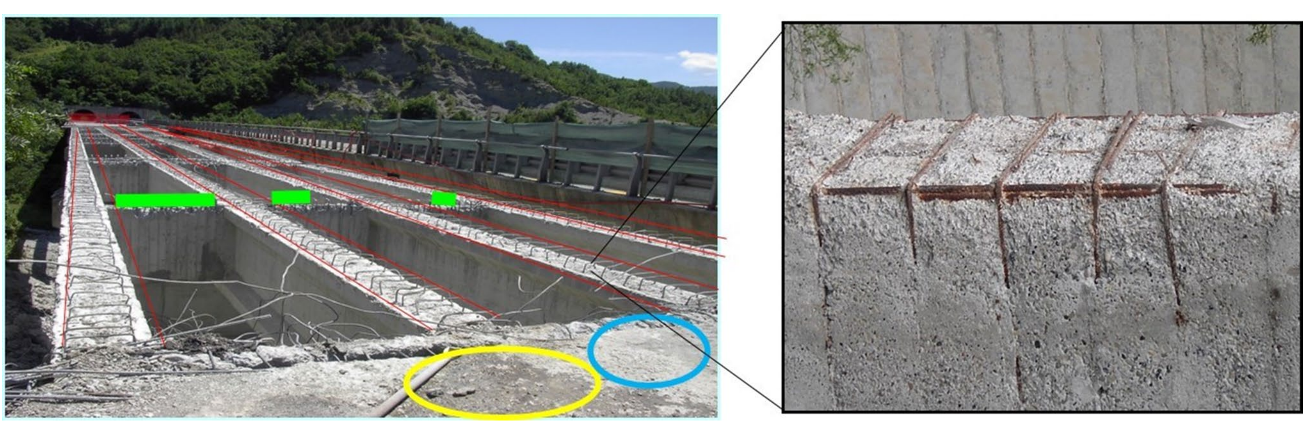

Fig. 1 Photo imaging of the viaduct in which different slabs were collected. Coloured in red the four longitudinal beams; coloured in green the orthogonal beams; coloured in yellow the clear layer of waterproofing materials; coloured in blue the dark asphalt layer; on the right pane the internal steel reinforcement

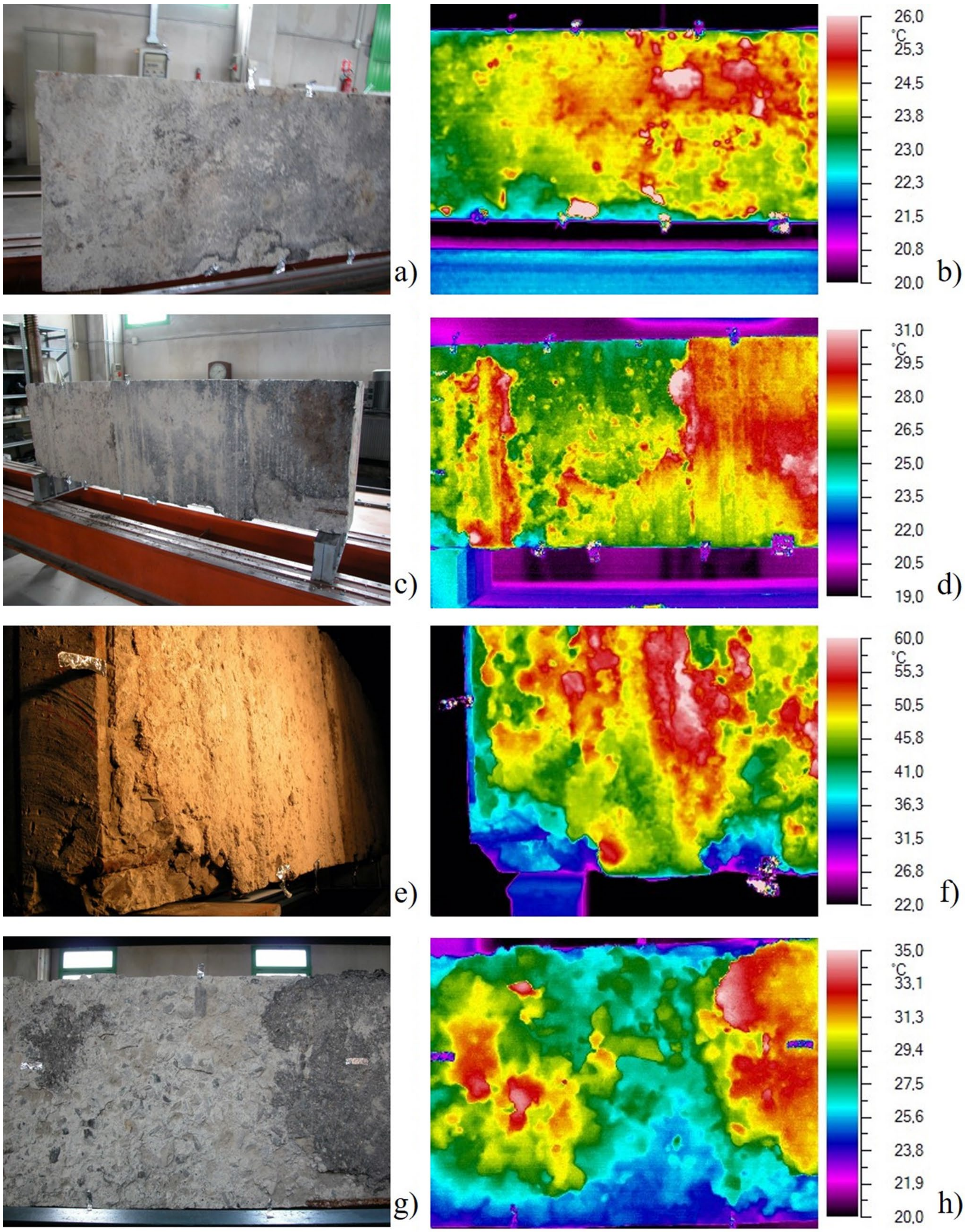

Fig. 2 Photo and thermographic images of the analysed samples: **a** and **b** sample L1; **c** and **d** sample L2; **e** and **f** sample L3; **g** and **h** sample L4. Images **a**, **c**, **e** and **g** represent the analysed samples at ambient temperature (a real photo of the sample collected); **b**, **d**, **f** and **h** the images of the analysed samples at different temperatures during heating cycles

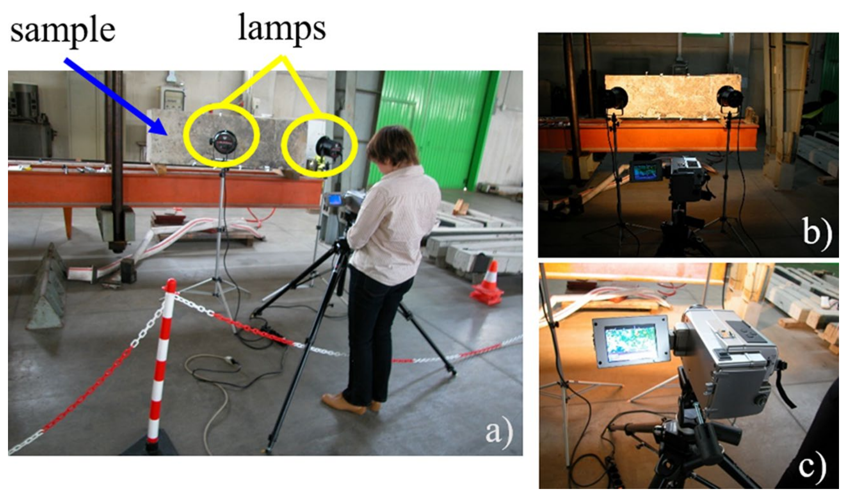

Fig. 3 Photo imaging of the thermographic investigation during the test analyses: **a** better explain the position of the two lamps (in the yellow circle) used to illuminate the sample (indicated by a blue arrow) and the operator with the thermographic instrument used; **b** photo imaging of the analysis; **c** photo imaging of the immediate results on the infrared thermal imaging camera

Table 1 Different steps of carrying out the thermographic analysis during heating and cooling phases

Sample name	Heating		Cooling	
	Distance from the lamp (m)	Image recording	Duration time after the lamps were turned off (m)	Image recording
L1	1.20	30 s for half an hour	20	Every 30 s
L2	0.90	60 s for an hour	20	Every 60 s
L3	0.40	60 s for 35 min	20	Every 30 s
L4	0.60	60 s for 40 min	20	Every 60 s

compressive strength tests at the Structural Engineering Laboratory of the University of Ferrara. Three different kinds of samples were drilled through the entire thickness of the slab and shaped to make them suitable for the test.

The press used has a maximum loading capacity of 3000 kN, and the distance between press plates is about 330 mm, the piston stroke being about 60 mm. The two compressive plates of the testing machine have a diameter of about 290 mm and they allow to test concrete cubes with a side of about 100–150 and 200 mm and concrete cylinder samples with a diameter of up to 160 mm and a height of approximately 320 mm. The hydraulic unit, motorized and self-ventilated, is made up of a pump, filters, and safety valves to comply with current safety standards. The load actuator's data are digitally recorded so that the load peak value can be detected.

Compressive tests were performed on the samples collected. The samples were subjected to loading and unloading cycles by the following steps: a first load cycle up to 1/3 of the expected failure load, a second load cycle at 2/3 of the expected failure load, and a third load ramp-up to the expected failure load. Before starting to load the samples, each sample was placed perfectly in the centre of the press plate to allow a uniform stress distribution.

In addition to the compressive tests, Ultrasonic Pulse Velocity (UPV) tests were also carried out on the samples to determine the propagation velocity within the material, which is dependent on the structure and the density of the material, as micro-cracks and voids slow down the elastic wave velocity. The UPV measurements were carried out in different directions: parallel and perpendicular to the direction of the steel bars placed inside the sample to define how the bars can be related to the formation of fractures. UPV were measured during the loading and unloading steps of the compressive tests in order to better understand how this velocity is related to the damage level and fractures induced by the test. The vertical deformations undergone by the sample during the compressive phase were measured as well.

2.3 Chemical characterization

Observation on the thin section of the samples was conducted using a transmitted light polarized microscopy (BX51 Olympus, Tokyo, Japan). The optical transmitted light microscopy (OTLM) is one of the fundamental and widely used techniques for the study of minerals and rocks. In this specific work, OTLM provides information about the presence of fractures, discontinuity in the binder, lithological composition of aggregates, and their chemical and physical alteration [37]. Through these observations, it was possible to study the nature of the aggregates used for the production of concrete and to understand how suitable these materials are to give concrete durability and the proper mechanical characteristics. The thin sections were obtained from a slice cut in the lower part and in the upper part of different cylindrical samples.

3 Results and discussions

An attempt was made to understand the relationships between the mechanical characteristics of concrete, in terms of durability, and the nature of cement paste and aggregates.

3.1 Mechanical characterization of the samples

Thermographic analyses were useful to understand how deep the damage was in the slabs and to detect any detachment of the asphalt [38], and of the underlying waterproofing binder, from them. These investigations were useful to detect the areas where to sample and they can support the general framework of a retrofitting intervention [39]. The causes of the detachment of the asphalt could be natural, such as temperature variations and precipitation [40–42], or anthropogenic caused by humans [43]. The thermal excursions involved continuous heating and cooling of the conglomerate, which made it more elastic and deformable in hot weather and more rigid and brittle in cold weather [44]. Over time, these processes promoted the formation of cracks. Both snow and rain precipitations lead to a further worsening of the concrete slabs as the water creeps into the cracks widening them [45, 46]. The water, due to the continuous passage of vehicles, increased structural failure and therefore favoured the formation of holes [47]. The anthropogenic causes, on the other hand, concerned the use of poor materials and/or incorrect application techniques, for example laying the road surface on an existing surface without having it adequately removed or worse still directly on the ground.

Besides, thermographic results allowed to better understand the important relationship between deterioration and temperatures, which is an important problem. The cyclic variations of the temperature, for example from winter to summer, cause granulometric disintegration of the concrete (thermal stress) [48, 49]. Zhai et al. [50] showed that chemical and physical changes take place in both the cement paste and the aggregates and that the changes are different at different levels of temperature [51, 52]. The deterioration of the concrete slabs is a very important phenomenon to be monitored because it requires cortical restoration interventions to reconstruct the damaged parts, eliminate cracks and protect the underlying structures from the penetration of substances capable of corroding the reinforcing rods [53, 54].

The processing of thermographic images produced sequences relating to the heating and cooling cycles. From these sequences, horizontal heterogeneities emerge due to the different adhesion of the asphalt on the surface of the slabs and to local conditions of degradation of the reinforcement. The pictures of Fig. 2 show different images for each analysed sample at different temperatures (Fig. 2b, d, f and h). In these images, you can see the areas where the heat is most accumulated and emitted to a greater extent (warmer areas); these correspond to the areas where the asphalt layer has been completely removed due to degradation, which can be caused by different factors: atmospheric conditions [55, 56]; chemical and physical attacks [57, 58]; friction due to the movement of cars [59]. Related to the physical deterioration, the effects of temperature on the structural quality of the concrete slabs (micro-cracking and micro-cracking) were also observed [60, 61], because the cyclic variation of the temperature causes granulometric disintegration of the concrete [62].

The performed compressive tests provided the load value of the samples at failure. The expected failure load value was experimentally estimated. The results showed a good strength level unless the concrete undergoes several load cycles. By processing the deformation data and relating them to the applied load, binary graphs were obtained in which the loading and unloading cycles and the failure load are highlighted. The occurrence of failure is evidenced by a sudden drop in compression load. In order to point out the effects of load cycles, the samples were drilled from portions of deck slab taken in zones with different levels of damage induced by vehicle traffic.

The graph of Fig. 4a shows that in the sample subjected to a low number of cycles, failure is not attained even for a load value equal to 300 KN. When increasing the number of load cycles, a smaller failure load (about 160 KN) is recorded as shown in Fig. 4b. Finally, Fig. 4c shows that for a high number of load cycles, the failure load breaks down to 120 KN circa. By applying loading cycles on the concrete sample, it is noted that the load–displacement curve slope varies its inclination during the loading and unloading phases due to the arising of microcracks. This behaviour becomes more evident as the number of cycles increases.

The UPV method was generally used as a non-destructive test in the ASTM standard [63] for the evaluation of the quality of the concrete slab [64, 65]. Ultrasonic pulse velocity (UPV) tests could be indicative of the level of damage in the concrete slabs [66, 67]. The measurements on the samples have shown interesting results, reported in Table 2. The UPV were measured in the longitudinal direction, along with the height of the specimen, and in the transversal direction at the top, central and bottom positions of each specimen. From the obtained data, it can be

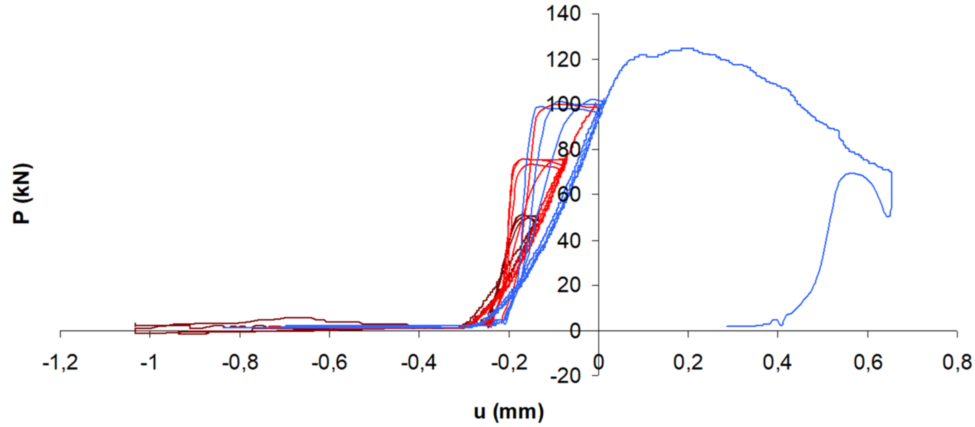

Fig. 4 Compressive tests of samples subjected to loading and unloading cycles: **a** low number of cycles; **b** medium number of cycles; **c** high number of cycles

Table 2 UPV measured for the concrete slab samples (m/s) on the top, central and on the bottom of the section analysed for each samples

Sample	Along the height	Top section	Central section	Bottom section
A 4–6	3900	3100	2100	2100
B 4–1	4400	2000	2900	4000
B 4–2	3800	2500	3500	–
C 4–7	2000	2200	2200	3000

noticed that except for sample A4-6 in which the values are similar in all measurement directions, in the samples B4-1 and C4-7 the UPV values are significantly higher in the lower part of the specimen, proving that concrete damage is generally localized in the upper part of the slab.

The measurements obtained on the samples analysed confirmed the processes of microcracks formation [68, 69], which was more evident on the deck slab areas most affected by degradation, due to atmospheric and chemical attacks, besides intensity and frequency of vehicle traffic.

3.2 Mineralogical characterization of the samples

The macroscopic analysis of cylindrical cores highlighted heterogeneity in the distribution, size, and shape of the aggregates used to produce the concrete. Figure 5a shows the presence of different sizes of clasts (coloured in red), while Fig. 5b shows that most of the clasts have sharp edges (coloured in red).

The microscopy observations on thin sections obtained from the samples were useful for determining the nature of the aggregates present in the concrete and for determining the possible relationships between the cement matrix and the aggregates themselves.

In the thin sections obtained from the upper part of the cylindrical samples analysed there are clasts of micritic

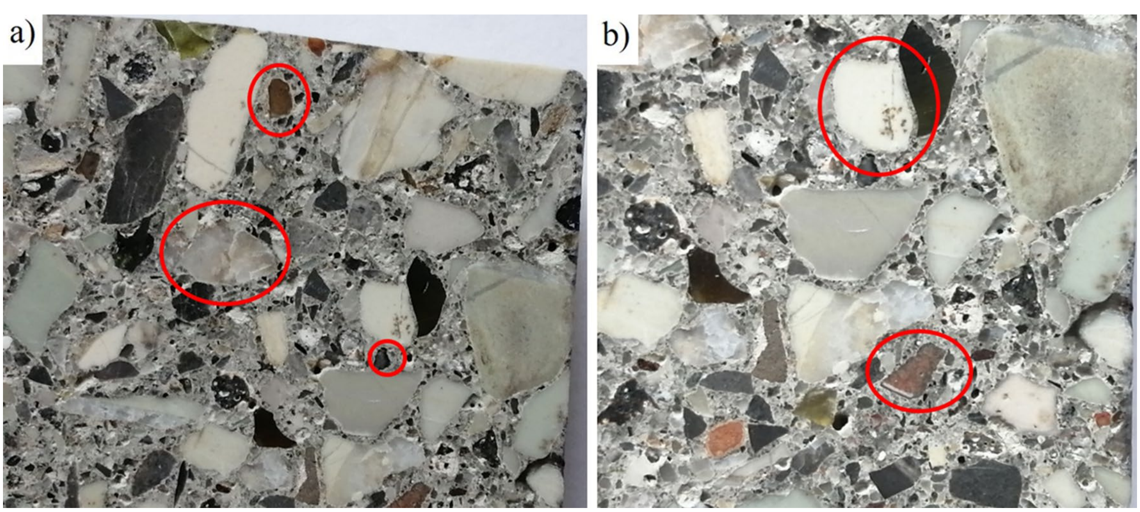

Fig. 5 Macroscopic characterization of the samples collected: **a** clasts of different size; **b** clasts of different shape

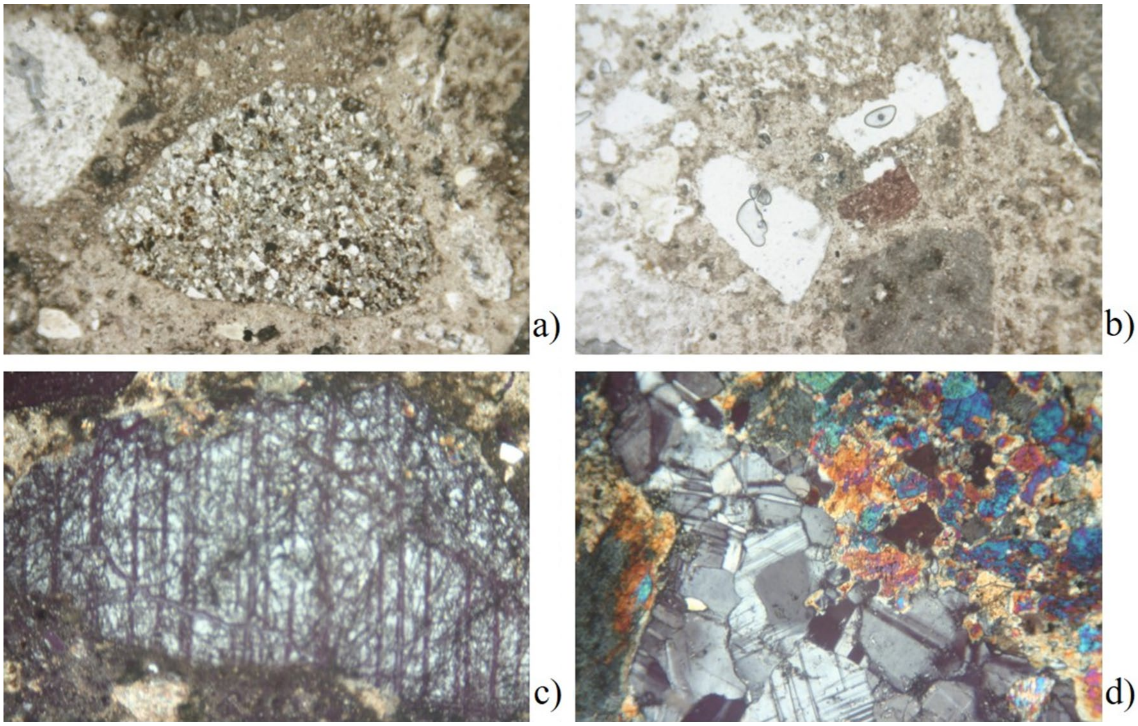

Fig. 6 Microscopic characterization of the different type of samples analysed by transmitted light polarized microscopy: **a** thin section obtained in the upper part; **b** thin section obtained in the lower part; **c** ophycalcites observed at crossed nicols; **d** metamorphic minerals observed at crossed nicols

limestone with very large bioclasts (example in Figs. 6a). Immersed in a silicate cement paste there are fragments of metamorphic rocks, probably marble. The edges between the larger aggregates and the matrix appear well defined. In some portions, minerals of alteration of the ophycalcites are found (an example is shown in Fig. 6c); other elongated portions of spatic calcite are observed.

Figure 6b shows an example of a thin section image obtained from the lower part of the cylindrical samples analysed. There are clasts of microclastic limestone with bioclasts and minerals of altered ophycalcite. There are smaller portions where fragments of quartz sand and fragments of metamorphic rocks are found. Small-sized portions of a metamorphic nature (marble and ophycalcite) and quartzarenite are recognized. There is a calcareous matrix with the presence of microfossils; small aggregates of micritic limestone have veins of spatic calcite. In some thin sections, the presence of garnets surrounded by alteration of ophycalcite in phyllosilicates is evidence of the use of metamorphic rocks for the aggregates of this concrete.

The study with transmitted light microscopy allowed to better recognize the lithology present in the collected samples. From the analysis results, it is possible to assume that the aggregates do not come from the area where the viaduct is located: they are composed of heterogeneous materials with very different hardness and there is a limited presence of fragments of metamorphic rocks (an example is shown in Fig. 6d). To determine the area of origin, we must research an area in which ophiolites emerge. Among the possible closer regions, we can make the hypothesis of the Futa pass (a pass of the Tuscan-Emilian Apennines in the province of Florence, in the Tuscany region), not far from the position of the considered viaduct. There are gaps between the ophthalmic and limestone aggregates and cement, which denote the tendency of these aggregates to detach, even if the physical–mechanical tests carried out in the central part of the less degraded cylindrical samples showed a good rheological behaviour [70, 71]. The presence of larger aggregates in the upper part of the cores is a negative detail, in fact, under the loadings to which a viaduct is subjected (traffic, etc.) the matrix detaches itself from the pebbles and pulverizes.

4 Discussion

Among the most important distresses of asphaltic pavements there is moisture sensitivity of an asphalt mixture. Although the effect of moisture on asphalt mixtures, unlike the traffic loading and thermal stress, is not considered as a major solicitation, penetration of moisture through the asphalt mixtures can increase the pavements' vulnerability to the other two solicitations [72]. Apart from the definition of moisture damage and the mechanisms of its formation in asphalt concrete, there are some factors related to the constitutive parts of the mixture and to the prevailing environmental conditions that can have a profound effect on expediting or impedance of moisture damage that will be discussed throughout the section [73].

Thermographic analyses have shown that the cause of the detachment of the asphalt has mainly a natural origin, due to temperature variations and precipitation, with a secondary cause in the anthropogenic impact [74]. The thermal excursions, with alternate heating and cooling, made the asphalt more elastic and deformable in hot weather and more rigid and brittle in cold weather [75–77]. Over time, these processes promoted the formation of cracks [78, 79] and both snow and rain precipitations lead to a further worsening of the concrete slabs. The water, due to the continuous passage of vehicles, increased structural failure favouring the formation of holes. On the other hand, the use of poor materials and/or incorrect application techniques, worsening the situation.

Rocha and Povoas [74] underlying that thermographic test is as a real alternative for the detection of defects in the reinforced concrete, being more effective the more superficial these anomalies, but depending on the work to be done, it is necessary to contemplate some considerations to obtain better results, so we add mechanical tests which shown a good quality concrete in terms of strength but, when subjected to cyclic loading, the ultimate strength level tends to decrease considerably due to the progressive formation of microcracks [80]. The UPV method was influenced by the concrete mixture characteristics, which could lead to ambiguous interpretation of the results. The measurements obtained on the samples analysed confirmed the processes of microcracks formation, more evident on the deck slab areas affected by atmospheric and chemical attack degradation, besides intensity and frequency of vehicle traffic [81, 82]. The localization of materials' micro-cracking could precede the catastrophic failure of the concrete slabs engineering structures; therefore, the characterization of the damage is of essential importance for structural instability monitoring.

The deterioration of the reinforced concrete could be done to different causes as described in the Introduction: chemical attacks, atmospheric agents, or intensive use of vehicles. It is impossible to define a single cause, but the deterioration is due to a set of causes. Corrosion of reinforcing steel is one of the main causes of deterioration of reinforced concrete, structures and affects both ultimate and serviceability conditions. Its effects include cracking and spalling of the concrete cover, reduction and loss of bond between concrete and corroding reinforcement, and reduction of the cross-sectional area of the reinforcing steel [83].

Numerous experimental studies have investigated the effects of corrosion of materials such as on steel bars [84] and steel–concrete bond [85]. There have also been studies at a structural level, relative for example to the flexural behaviour of beams [86] and columns [87].

Also, the mineralogical and petrographic composition of which the material is made is very important, because if of good quality it guarantees the contrast towards degradation, while if of heterogeneous quality or very variable between them, it can lead to an increase in fractures or micro-cracking if subject to the causes of explained above.

5 Conclusion

The slab analysed in this study has been mixed around the 1960 and the life of the structure is overpassed the service life design and the history of loads is very important for its evolution. For this reason, this work has provided information about the relation between concrete damage level and mechanical behaviour. It also highlighted the importance of nature, size, and distribution of the aggregates, since the durability characteristics of concrete depend on its composition.

This work is the result of an integrated study and an interdisciplinary approach between the Department of Physics and Earth Sciences and the Engineering Department of the University of Ferrara, in which not only engineering analyses were used but also mineralogical and petrographic characterization of the material to better explain the microcracking phenomena that could be one of the principal causes of the damage of the reinforced concrete. It is now well-established that the multidisciplinary approach is necessary for the study of cultural heritage degradation, but it is also important in the study of the degradation of large public works, such as viaducts and highway pavements.

This paper would be an example of an integrated study approach between engineering techniques and mineralogical-petrographic methodologies, usually applied to the study of natural stone, for better understanding the deterioration mechanism of concrete in order to improve an integrated model for the inventions.

Authors' contributions Conceptualization was done by M, A, C, M and V; Data curation was done by M, A, and M; Formal analysis was done by M and M; Funding acquisition was done by V; Investigation was done by M, T, A, C, M, and V; Methodology was done by M, T, M, and V; Resources was done by C and V; Supervision was done by M, A, and V; Writing—original draft was done by M, T, A, M, and V; Writing—review and editing was done by M, T, A, M, and V.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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