Assessment of material degradation based on microcores testing

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ABSTRACT: The paper presents the results of testing of small microcore specimens using Compact Diagnostic Test (CoDiT). Measurement of the evolution of strength and elastic properties of limestone is used to demonstrate the applicability of microcores testing for the assessment of actual state of degradation of heritage construction materials. The measurements are performed on artificially aged Portland Limestone, widely used as monuments building material, e.g. in London. Microcore specimens are drilled out of samples which undergone the series of cycles of accelerated Freeze and Thaw (F/T) ageing. Among the measured parameters there are the velocity of ultrasonic waves and the flexural, tensile and compressive strengths of the material after various number of F/T cycles. Results show that specimens drilled of the more aged sample are stronger than less weathered material, which is in agreement with the results of the previous non-destructive testing of large samples done in another laboratory. Based on the CoDiT image analysis, the effect is attributed to large material inhomogeneity which is so important that it overpasses any possible material degradation introduced by the applied weathering procedure.

1 INTRODUCTION

Direct measurements of material strength degradation are done very rarely as they are harmful to the monument if done according to civil engineering standards. However small samples of historical materials are, or can be, available if microcores are drilled out of masonry during installation of sensors and other elements, like for example scaffoldings. Testing of small samples of historical construction materials in the form of microcores is a new experimental field having only a few years history. Kasal reported the drilling of 5 mm microcores using 10 mm core drill for evaluation of strength of wood structural members (Kasal 2003). The method was further extended for sampling of non-cylindrical wood specimens and tensile strength and diametral compression loading was studied (Kasal et al., 2003). Hydraulic portable press for diametral compression of wood microcores developed at the Institute of Theoretical and Applied Mechanics, Academy of Sciences of Czech Republic, was exhibited during VII European Conference “SAUVEUR” in June 2006, in Prague.

In parallel, a technology of microcore testing of masonry materials has been developed, inspired by the drilling resistance measurement method DRMS (Tiano et al. 2000). This method makes use of diamond drills with flat cutting surface and one of the main problems is zero rotational speed (and hence, cutting speed) in drill contact points positioned on the drill axis. A solution to this problem might be the application of core drills. A natural further conclusion was that one can use small microcore samples from every hole drilled with a small diameter core drills, not only in connection with the DRMS tests.

Next step in the development of small sample testing of historical masonry materials was the manufacturing of the equipment for drilling long microcores and development of the experimental procedures of microcore testing. This development was done in 2005 at the Institute of Fundamental Technological Research of Polish Academy of Sciences and first reported in (Skłodowski 2006a). In the same year the experimental procedure called Compact Diagnostic Test (CoDiT) was presented (Skłodowski 2006b) and a comparison of the results for standard size specimens and microcore specimens tests was done (Skłodowski 2006c).

The following report presents the results of measurements performed on microcores drilled out of samples of Portland Whitbed limestone weathered in laboratory by Freezing & Thawing (F/T) cycles. This artificial ageing procedure was done within the framework of European Commission research project MCDUR by researchers from Politecnico di Torino, DITAG – Land, Environment And Geo-Engineering Department (Bellopede & Manfredotti 2006). They also made non-destructive measurements of the elastic properties of the weathered limestone. Measurements of ultrasonic P-wave velocity, of Schmidt hammer rebound hardness and of DRMS were used. All three methods showed a rather unexpected result.
that specimen which undergone 120 FT cycles had better elastic properties than intact Portland specimens (Morandini & Marini 2005).

Present research using microcore testing by the Compact Diagnostic Test (CoDiT) procedure confirms the previous results and shows that not only elastic properties, but also strength properties of microcores drilled out of these previously tested samples of artificially aged limestone are much higher. However, the morphological analysis included in the CoDiT procedure suggests that this “strengthening effect” should rather be attributed to large material inhomogeneity than to the FT ageing process.

2 THE CODIT METHOD

Compact Diagnostic Test (CoDiT) is a sequence of experimental steps (Skłodowski 2006a) which serves to gain of a maximum knowledge from the investigations microcores. Such a sequence of measurements is non-destructive from the viewpoint of the monument if microcores are drilled out of masonry during installation works.

Consecutive steps of the CoDiT are:

Step 1. Draw a line to permanently mark the reference coordinates of the material within the structure e.g. the vertical plane crossing a hole to be drilled.
Step 2. Measure the velocity of propagation of surface wave (Rayleigh wave) along the marked the line and perpendicularly to it.
Step 3. Drill a hole with a core drill bit, preferably during installation works and take out a microcore.
Step 4. Flatten the core base which resulted after its breaking off and copy the line mark (from Step 1) on it and on the cylindrical side surface of the core.
Step 5. Measure the core dimensions and weigh the core.
Step 6. Record an image of the side wall of the core and analyse micro-cracks, pores and material inhomogeneities.
Step 7. Perform three-point bending test of the core in the plane marked. Two “half-cores” will come into being.
Step 8. Cut the half-cores to the desired length and measure the velocity of propagation of the longitudinal wave along the cores.
Step 9. Perform uniaxial compression test using one half-core (see Step 7).
Step 10. Perform diametral compression test of the other half-core along the originally vertical plane (comp. Step 1 and Step 7).

Destructive tests of Steps 9 and 10 can be modified as necessary. This is especially recommended when the number of microcores available for testing is greater than the one required for basic measurements. In such a case an uniaxial cyclic compression of one half-core and a creep test of the other might be of a special interest.

3 MATERIAL

The material is Portland Whitbed Limestone used in construction of historical buildings in UK. Well known examples of such constructions are St. Paul’s Cathedral in London and Sydmonton Court in Newbury. This limestone is a fine grained Jurassic stone composed in over 92 percent of calcite and less than 8 percent of quartz. Inside the material, shell fragments are deposited among calcium carbonate forming bands or are distributed randomly.

All Portland Whitbed Limestone samples were cut from the stone bed from Albion Independent quarry (Portland, UK) for the research purposes of the European 5Th Framework project MCDUR.

Figures 1–3 are microcore images showing examples of three typical cases. In Figure 1 a very few shell fragments localised far from each other is seen. Figure 2 shows large bands of hard material localised mostly parallel to the microcore axis. In the Figure 3 a large amount of small hard inclusions randomly distributed in stone can be seen.

The CoDiT procedure reveals not only these very different morphological compositions of the Portland
material. Mechanical tests included in the CoDiT procedure shows the consequences of these various material structures on elastic and strength properties of the tested specimens.

Figure 2. Unwrapped surface of the microcore specimen PW28 from the sample after 60 cycles of freezing & thawing.

Figure 3. Unwrapped surface of the microcore specimen PW48 from the sample after 120 cycles of freezing & thawing.

Table 1. FT procedure.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Description</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start</td>
<td>The saturated specimens are introduced into the freezing tank</td>
<td>( T_0 )</td>
</tr>
<tr>
<td>1</td>
<td>The temperature at the centre of the monitored specimen reaches (-10 \pm 2)°C</td>
<td>By ( T_0 + 2 ) h</td>
</tr>
<tr>
<td>2</td>
<td>The temperature at the centre of the monitored specimen remains at (-10 \pm 2)°C</td>
<td>( T_0 + 4 ) h</td>
</tr>
<tr>
<td>3</td>
<td>The specimens are introduced in the water bath and are totally immersed</td>
<td>By ( T_0 + 4.5 ) h</td>
</tr>
<tr>
<td>4</td>
<td>The temperature at the centre of the monitored specimen reaches ((20 \pm 5))°C</td>
<td>By ( T_0 + 6 ) h</td>
</tr>
<tr>
<td>End</td>
<td>The temperature at the centre of the monitored specimen remains at ((20 \pm 5))°C</td>
<td>( T_0 + 8 ) h</td>
</tr>
</tbody>
</table>

4 SPECIMENS

Specimens in the shape of microcores with the diameter of 6–6.5 mm and the length of 24–30 mm are used for measurement of several elastic and strength parameters of the tested material.

Figure 4 illustrates how the specimens are collected from the rectangular prismatic samples of Portland Whitbed limestone.

4.1 Weathering

Weathering of Portland Whitbed samples was done by Politecnico di Torino, DITAG – Land, Environment And Geo-Engineering Department (Bellopede & Manfredotti 2006) according to the procedure presented in Table 1.

4.2 Sampling of specimens

In the present research the microcores were drilled out of samples originally encoded as PW052 which
undergone 60 FT cycles and PW128 aged by 120 FT cycles. Microcores were drilled with their axis parallel to the limestone bedding plane. This allows to perform the measurements of the P-wave measurement, the uniaxial compression strength and the indirect tensile strength with deformation localisation along the bedding plane. Flexural strength could be measured perpendicular to the bedding.

As the first step, a set of lines parallel to bedding planes were marked on PW052 and PW128 samples to allow the unique identification of the direction of loads applied in measurement procedure. The second step before sampling was the measurement of the velocity of propagation of ultrasonic surface wave (Rayleigh wave) along the marked vertical lines and perpendicularly to them using edge probes (Skłodowski 2005). After this measurement, seven long microcores were drilled from each sample of limestone. Specimens length was about 27 mm and their diameter between 6 and 6.5 mm.

Reference samples of non-weathered limestone are the specimens reported in the previous author’s paper (Skłodowski 2006c).

Examples of each group of microcore specimens are shown in Figures 1–3 revealing the various internal composition of the limestone. It has happened that these various samples were used in previous FT weathering test, each sample being frozen applying different number of cycles. Assuming that freezing process cannot change material morphology so much, it can be sad that the weathering processes would have lower influence on material properties than differences between local properties of specimens used in each step of the FT test.

5 MEASUREMENT PROCEDURE

The microcore specimens prepared according to the above sampling method were subjected to the following testing procedure.

At first images of a side wall of the core were taken and combined, when necessary, into a single image of the unwrapped side surface of the core. Examples of such images are shown in Figures 1–3. This allowed analysis of specimen’s morphology and material inhomogeneity.

Next, the line marking from the microcore base was elongated onto its cylindrical side wall to keep the track of the specimen’s orientation during the other tests.

As the next step three-point bending test of the core was performed to measure limestone flexural strength (FS). Direction of loading was the same as that of the line marked on the core. This allowed to break the core perpendicularly to the material bedding. Resulting two sub-cores, marked with additional letters “a” and “b” (e.g bending of the specimen PW28 results in obtaining specimens PW28a & PW28b) were cut to flatten their bases and to obtain a short core of the length equal to the microcore diameter and a long core having the length equal to twice the diameter. After that, the propagation velocity of ultrasonic P-wave along the longer sub-cores was recorded. As the last two steps, the destructive tests of both sub-cores were done. Smaller cores were compressed along their diameter coinciding with the bedding plane to measure the indirect tensile strength (ITS) of the material and longer cores were used for uniaxial compressive strength measurement (UCS).

Strength measurements are done using a specially designed, hand operated, screw driven, mechanical loading device. Recorded load-displacement curves are based on strain gauge and LVDT sensor measurements, respectively. Analog signals are amplified, digitized online and stored in the connected PC.

6 RESULTS AND DISCUSSION

CoDiT results of limestone degradation assessment presented here belong to three groups. The first group are the results of optical analysis included in the CoDiT procedure. They are presented in the form of unwrapped cylindrical surface images of the microcore specimens given in Figures 1–3 and showing specimens morphology.

The analysis of post-critical deformation and crack formation is also performed in each mechanical test to make sure that deformation mechanisms are correct and hence that the strength measurements are reliable. Examples of these deformation modes are presented in Figure 5 where cracks developed in the Brazilian Test, in the uniaxial compression test and in the three-point bending test are shown for specimen PW29 after 60 FT cycles.

It can be seen in Figure 5 that for fine grained Portland Limestone the deformation mechanisms in all three tests are the same as in the case of testing standard full-size specimens.

Forty two mechanical tests of microcores were conducted including seven bending, seven diametral compression and seven uniaxial compression experiments for each of the weathered Portland samples. Stress-displacement curves were recorded during each mechanical test. Their examples are presented below in Figures 6–8. They are grouped in pairs to underline the differences recorded in the behaviour of the material from the sample after 60 FT cycles of weathering and that after 120 FT cycles.

Load-displacement curves for bending of Portland Limestone presented in Figure 6 show that the specimen drilled out of a more weathered sample can be even two times more tough than the specimen from a less aged material. Average difference in flexural strength is also very pronounced (Fig. 9) but not as high. It is worth to remind here that motivation for
the presented research was an unexpected high ultrasonic P-wave velocity, Schmidt hammer rebound hardness and drilling resistance recorded during previous research in another laboratory for the most weathered Portland specimens. Three-point bending test presented here confirms that the previous results are meaningful even if considered strange and unexpected.

The next loading tests are done using two sub-cores resulting from each bending tests as it can be seen in Figure 5. Before proceeding, the halves of a microcore are prepared for loading by cutting their ends to produce short and long cylindrical specimens with flat and parallel bases. Cutting length is 6–6.5 mm for short specimens used in Brazilian Test and about 12–13 mm for specimens used in uniaxial compression tests.

During diametral compression of short specimens it was possible to perform unloading-loading cycles in some of the experiments. Such load-displacement curves are presented in Figure 7 for the same microcore specimens for which experimental curves recorded during bending test are shown above. Again it can be seen that the specimen from the most weathered sample is much stronger than that from the less aged
material. This time the strength ratio between both specimens is less pronounced than in the case of bending and the average values of diametral compression ITS are even more close to each other.

Unloading-reloading curves can be used to get additional information about the stiffness of the specimens. Let us observe that higher stiffness of specimen made of more aged material shown at the bottom of Figure 7 can be seen even without thorough calculations. This again confirms the previous results of non-destructive tests.

Results from uniaxial compression tests of specimens from the other sub-cores show the same tendency which was observed in FS and ITS values. The strength of specimens drilled out of the sample which undergone 120 FT cycles is much greater than the strength of specimens from the sample weathered in 60 FT cycles.

Load-displacement curve in the upper part of the Figure 8 is the example of the test which was discarded due to an improper deformation mechanism of the specimen and, in consequence, too low ultimate load. This specimen was crushed in several places starting from its upper base forming several short shear cracks which reach about one third of the specimens height.

In the other uniaxial compression tests the proportion between the recorded ultimate loads for both weathered limestone specimens were close to 2:1 instead of 3:1 which could be suggested by the curves presented in Figure 8.

The analysis is based on the measurement of five parameters. Two of them are the indexes which characterize the elastic properties of limestone. These are the squared values of P-wave and R-wave velocities \( V^2_P \) and \( V^2_R \) which are proportional to the modulus of linear elasticity (Landau & Lifschitz 1986). The three others are the measured values of FS, ITS and UCS. Average values of these parameters are presented in Figure 9 where ordinate axis takes the dimension of MPa or \( \text{km}^2/\text{s}^2 \) depending on the index type.

Figure 9 illustrates in a single diagram the fact that the trends in all the measured elastic and strength properties are the same, thus showing that this is a predominant tendency. The presented results are average values recorded for all the tested microcore specimens from the weathered samples. It is easily seen that one sample of the limestone has much better properties than the other one. It is also clear that the differences are so meaningful that they overpass any possible material degradation introduced by the applied weathering procedure. A possible explanation of this phenomenon can be attributed to the material morphology and internal composition of the specimens. To discuss the problem let us look at Figures 1–3.

Specimen PW28 from Figure 2 is machined from a sample which undergone medium ageing of 60 FT cycles. The unwrapped surface of the specimen shows...
a large shell inclusion which acts as a strengthening element within the specimen on the one hand but also as a stress concentrator on the other. As the result of this inhomogeneity, a local increase of flexural strength is observed because the shell stripe is almost parallel to stress trajectories in bending. Also the P-wave time of flight decreases as the wave travels the part of its distance choosing faster and easier path through the shell. But in diametral compression and in uniaxial compression tests the specimen fracture is probably activated along contact surfaces of oolite limestone and the shell due to incompatibility of strains. Thus the strength increase is smaller than in the more homogeneous PW48 specimen.

Specimen PW6 shown in Figure 1 is machined from an almost homogeneous sample of limestone composed mostly of calcite. This sample was not exposed to frost ageing but a relatively low strength of this intact material results from its mineralogical composition with predominant weak calcite grains and no strengthening effect due to almost complete lack of shell inclusions.

7 CONCLUSIONS

The main conclusion is that the CoDiT method confirms the results of previous research showing that the sample which undergone 120 cycles of FT weathering has the best mechanical properties. However, the optical analysis included in the CoDiT procedure suggests that this effect should be attributed to morphological composition of the samples of limestone rather than to the weathering processes.

Degradation of Portland Limestone due to consecutive freezing and thawing is much lower than the material inhomogeneities. These inhomogeneities are large both in the sense of morphological inhomogeneity and also local variations of elastic and strength material properties.

The Compact Diagnostic Test, unlike other research methods used for assessment of material degradation, provides the information on the actual elastic and strength material properties and shows that they have usually a similar trend of qualitative correspondence.

The advantage of the CoDiT method is that the small size of the specimen makes it possible to look at the material structure from a relatively close perspective. This makes it possible not only to state the mechanical properties of the material, but also to see what morphological structure gave rise to these properties.

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REFERENCES


