Effect of stylolites on the durability of building stones: two case studies

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The mechanical properties and the durability of natural building stones are influenced to a large extent by inherent inhomogeneities. One of such inhomogeneities is a stylolite, particularly when it occurs in carbonate-rich rocks. Stylolites are irregular surfaces in which small tooth-like projections on one side of the surface fit into cavities of like shape on the other side. Many stylolitic carbonate rocks are generally dense and sound, and may perform excellently when used as facing stones or tiles. However, there are other types that are of inferior quality due to the type of materials filling the stylolites. To the naked eye, such rocks may appear dense, homogenous and impermeable, but on a microscale, the stylolites may contain porous, permeable and water-sensitive materials, such as smectites that can adversely affect the durability of such rocks when exposed to the atmosphere. Experience shows that the use of an integrated method, consisting of traditional physical, non-destructive and durability tests, in combination with optical microscopy and X-ray diffraction analysis, often offers an invaluable means of evaluating the quality of such materials. In this paper, the use of such an integrated method to assess damage due stylolites in two separate natural stones is presented and discussed.

Key words: building stones, stylolites, microscopy, inhomogeneities, durability

1 Introduction

1.1 Definition and structure

Stylolites are irregular surfaces observed mostly in porous sandstones and limestones. An important characteristic of these structures is their preferred orientation: most stylolites tend to develop parallel to bedding planes, in which small tooth-like projections on one side of the surface fit into cavities of like shape on the other side as shown in Figure 1 (Lepedes 1978).

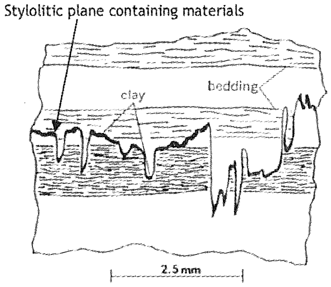

Fig.1. Schematic illustration of the occurrence of a stylolite in a seam of limestone (Lepedes 1978).

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According to Bates and Jackson (1987), stylolites can be described as surfaces of contact, that are marked by an irregular interlocking penetration of two sides, whereby the columns, pits, and tooth-like projections on one side fit into their counterparts on the other. When viewed in cross-section, stylolites resemble sutures; in other words, a cross-section of a typical stylolite would be similar to a profile of a series of high ridges and low valleys with many peaks and valleys being about the same amplitude.

Pettijohn (1957), on the other hand considers a stylolite as a seam, and describes it as a surface marked by interlocking or mutual interpenetration of the two sides. The teethlike projections of one side fit into sockets of like dimension on the other. In cross-section, the stylolite surface resembles a suture.

Stylolites are considered by some geologists as primary structures formed in the sediment before consolidation. However, most geologists consider stylolites to have formed after lithification, and therefore to be secondary structures produced by differential solution of material along a parting or fracture in the rock. A well-developed stylolite may appear as a thin irregular argillaceous parting. Most stylolites cut across many structures in the rocks they traverse, including fossils and oolites. Commonly these structures show truncation or partial solution along the stylolite seam.

1.2 Process of formation

Stylolites are supposedly formed diagenetically in an already lithified rock by differential vertical movement under pressure, accompanied by solution – the so-called process of dissolution creep or pressure solution (Davis and Reynolds 1996). This process involves selective removal, transport and precipitation of material through fluid films along grain boundaries or pore fluids between grains. The presence of a fluid phase along the grain boundaries and in pores between grains greatly increases the efficiency with which material can be removed from the sites of high compressive stress and transported concomitantly to those of lower stress (Friedman and Sanders 1972). As dissolution creep proceeds, sites that continuously experience dissolution become favourable sites for the formation of stylolites and the accumulation of insoluble materials, such as clays, mica, carbonaceous organic residue and oxides of iron and manganese (Friedman and Sanders 1972, Davis and Reynolds 1996). Usually the material dissolved in the fluid is re-precipitated locally on existing minerals in the rock. The zones where the dark, insoluble residues accumulate are usually called stylolitic halos (Davis and Reynolds 1996).

1.3 Origin, properties and occurrence

Stylolites are formed in consolidated rocks by the process of pressure-solution since in most cases they occur transverse to the bedding plane of the host rock and often cut across post-consolidated features such as veins (Davis and Reynolds 1996). The geometrical relations between stylolites and such structures as fossils, oolites, bedding and veins, demand removal of considerable rock material.

The relief or the amplitudes of the peaks and valleys of stylolites varies from a fraction of a millimetre to ten or twenty centimetres (Pettijohn 1957, Lepedes 1978). The width of the teeth or columns and the corresponding sockets into which they fit, varies with the height or amplitude of the structures (Figure 1). The stylolitic seam is traceable for varying distances – a few centimetres to several metres. The stylolitic surface itself is marked by a thin deposit of relatively insoluble material – a material, which is a very minor constituent of the rock in which the stylolite occurs (Pettijohn, 1957, Lepedes 1978, Bates and Jackson 1987). The residue on the seams in carbonate rocks is largely clay, in part carbonaceous and in part ferruginous. Particles of quartz, silt or fine sand tend to collect along the seam. The stylolites of some sandstones have a parting of coaly matter, while those of quartzites are marked by iron oxides (Larsen and Chilingar 1957, Pettijohn 1957). As mentioned previously, stylolites are most commonly parallel to the bedding, though there are stylolites that are transverse, even perpendicular to the bedding plane. In general, the columns are normal to the stylolitic surface, though there are a few cases in which the columns are vertical even though the seam is inclined.

Stylolites occur in many kinds of rocks. They are most common in hard well-cemented carbonate rocks, mostly limestones, dolomites, travertine and bedded siderites, but they are also present in other rocks, such as sandstones, quartzites, gypsum beds and cherts. They are present in metamorphosed carbonates, especially in marbles. Stylolites are known to occur also in non-carbonate rocks, such as sandstones and quartzites. In quartzites, in particular, they are reported to commonly occur normal to the bedding plane rather than parallel to it. Stylolites also occur in gypsum deposits and may occur probably in anhydrite and salt. It is reported that in all cases, the stylolites occur only in relatively "pure" or homogenous rocks. The quartzites with stylolites are high-silica quartzites. The limestones and marbles are high carbonate rocks. Stylolites do not occur in "impure" quartzites and carbonate rocks. Stylolites have never been found in shales (Pettijohn 1957).

1.4 Significance

One significant characteristics of stylolites is that along almost all stylolite seams, planes or surfaces, there is a commonly thin dark grey residual deposit or layer of argillaceous or carbonaceous material composed mainly of quartz, clay, silt or oxides of iron and manganese, which are highly acid insoluble materials as compared with the rock proper (Pettijohn 1957, Lepedes 1978, Bates and Jackson, 1987).

Rocks containing stylolites are used almost as much as non-stylolitic rocks in the building and construction industry. They are mostly used as facing, ornamental and decorative stones and occasionally as aggregates for concrete provided the material filling the stylolitic seams are not sensitive to moisture. When the material filling the planes of the stylolites are rich in expansive or swelling clay minerals of the smectite group, such as montmorillonite or hectorite, excessive absorption of water by the clay can cause the rock to disintegrate through alternating wetting and drying or through frost attack when subjected to typical cold temperate outdoor conditions. When the residues in the stylolitic seams contain non-expansive or less expansive clay minerals, such as kaolinite or illite, the rock is then relatively insensitive to moisture changes and therefore (all other things being equal) resistant to disintegration when exposed to outdoor conditions. The presence of swelling clay minerals in the stylolitic seams can usually be detected by means X-ray diffraction analysis in combination with the methylene blue adsorption test (Verhoef 1992), on portions of rock samples containing the stylolitic seams.

Stylolites give stones special aesthetic significance. This is the reason why sometimes they are selected above other non-stylolitic stones for use as decorative stones. When sawn and carefully polished, most stylolitic stones exhibit their distinct, beautiful sutures, which make them attractive for decorative and ornamental purposes. Typical carbonate rocks containing stylolites that are commonly used as facing or decorative stones in buildings include travertine, limestones and marbles.

2 Methods of investigation

2.1 General

There are several types of diagnostic investigations depending on the aim of the investigation. Usually, complete diagnosis of the causes of deterioration of natural stones in a building involves a series of multi-disciplinary studies, which starts from field inspection of the building and removal of samples for laboratory studies. This is followed by laboratory studies, which usually includes an integrated microscopic analysis and supplementary tests. The intent of the field inspection is to acquire information on the structure, in order to formulate a first idea about possible deterioration mechanisms, to locate areas for sampling and to remove core samples for laboratory studies.
The integrated microscopic analysis, which deals with detailed studies on the cored samples to establish the real causes of the distress, consists of visual examination of the samples with the aid of a stereomicroscope, detailed microscopic studies, usually by means of polarising and fluorescent microscopy (PFM) and, where necessary, scanning electron microscopy combined with energy dispersive X-ray spectroscopy (SEM-EDS). Each phase of the investigation has a specific purpose, which is usually controlled by the budget and the time available. In this paper, only those aspects dealing with the integrated microscopic analysis in the laboratory is presented. A systematic approach of the method is presented in Fig. 2.

2.2 XRD analysis

X-ray diffraction analysis involves determination of the mineralogy of the crystalline solid phases in a material with the aid of X-ray diffractometer. The analysis is usually performed on small, yet representative portions of the specimens. In the present study, a Philips PW 3020 instrument, with vertical graphite monochromatized, CuKα-radiation was used. The specimens were first ground to a suitable fineness (usually < 63 μm) before placing in the instrument. The specimens were then mounted onto stubs and placed in the diffractometer for analysis. Each analysis was performed within two hours and covered diffraction angles of 5-120 2θ using a step size of 0.05 $°2\theta$ and a receiving slit of 0.1 $°2\theta$. The detection limit of the diffractometer was about 3 % by mass.

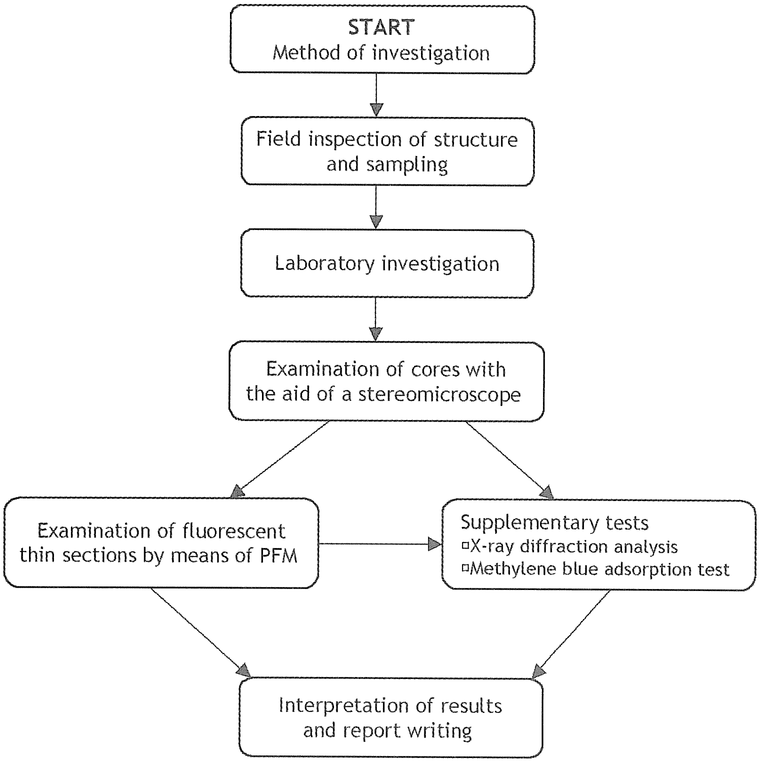

Fig. 2. Systematic approach of a simplified method of diagnosing the causes of damage of natural stones in a building.

3 Case studies

3.1 *Limestone slabs in pre-fabricated elements*

3.1.1 Problem

This case study was concerned with sawn limestone slabs containing stylolites that had already been used as facing stones in prefabricated concrete elements for a multi-storey office building. In the course of production of the prefabricated concrete elements, a number of the limestone slabs that had already been used in the prefabricated concrete elements and exposed to outdoor conditions started disintegrating along the planes of the stylolites. Some of the disintegrating layers of the limestone slabs could easily be removed along the planes of the stylolites by means of a gentle tap on a chisel when the damage was noticed. The concrete elements containing the disintegrating limestone slabs had at that of damage been exposed to outdoor conditions for barely two weeks after fabrication. These outdoor conditions were very similar to the conditions that the slabs would have been exposed to in their eventual use. On the basis of the observations made, an investigation was initiated aimed at establishing the cause of the disintegration.

3.1.2 Investigation

The first part of the investigation consisted of a series of visual inspections of some of the limestone slabs that had been sawn and stored under two separate environmental conditions but not yet used in the prefabricated elements. This was followed by field inspections of similar slabs that had already been used in the prefabricated concrete elements and exposed to outdoor weather conditions. After these inspections, a series laboratory tests was set up, which was designed to determine any flaws, defects or weak zones in the slabs and to predict the long-term durability characteristics of the slabs. The tests performed included an optical microscopic study by means of polarising and UV-fluorescent microscopy, a methylene-blue test (for the detection of swelling clay minerals (Verhoef 1992)) and X-ray diffraction analysis were performed on samples of the limestone slabs containing some of the stylolites. In addition, a series of supplementary tests, including a 'hammer test', an ultrasonic pulse velocity test, a Grindo Sonic test and an autoclave test was carried out to support the optical microscopic analysis.

The dimensions of the slab samples that were used for the laboratory investigations were variable. The largest and the smallest slabs measured 735 x 532 x 30 mm^3 and 631 x 461 x 24 mm^3, respectively. The sampling was carried out on slabs that had been packed in crates and exposed to two different environmental conditions:

- stone slabs that had been stored in crates in a hall under controlled conditions of about 15-2^{0}C and about 65-80% relative humidity;
- stone slabs that had been stored in crates and exposed to atmospheric conditions outside the hall.

An overview of a set of the limestone slab used for the laboratory investigation is shown in Fig. 3.

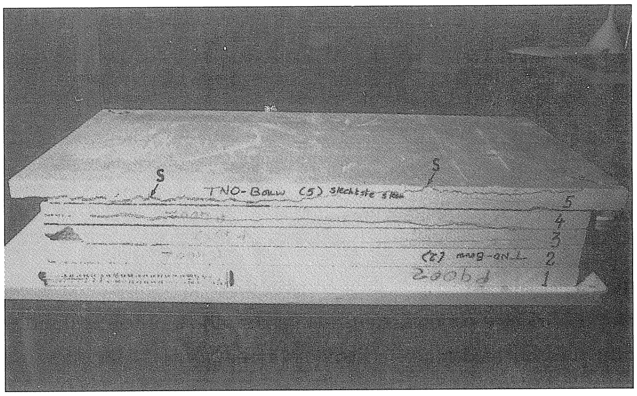

Fig. 3. Overview of a set of the limestone slab samples used for the laboratory investigation. S = stylolite

3.1.3 Results

a. Visual inspection

A number of the slabs in the prefabricated concrete elements (at least about 10-20) was found to have partially disintegrated or was in the process of disintegration. The disintegration was almost always in the form of spalling or flaking along the planes of the stylolites in the slabs (Fig. 4).

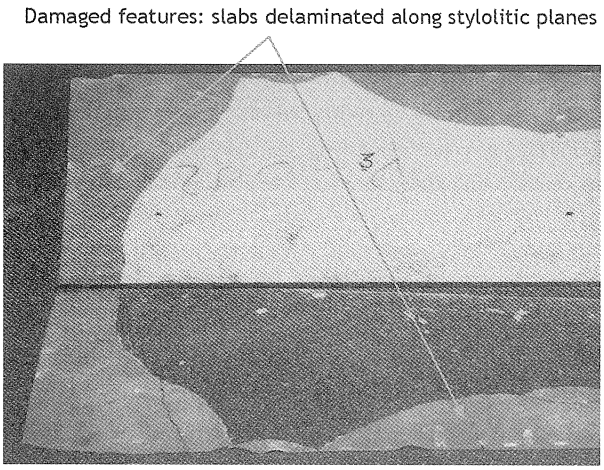

Fig. 4. Overview of a sample of the limestone slab in the field showing delamination along inherent stylolitic planes in the slab.

All the disintegrating slabs involved those that contained clay-rich stylolites and the stylolites were also exposed at the polished surface. The sound produced from such slabs from the gentle hammer taps also suggested that they contained loosely bonded layers. This aspect was also applicable to some of the slabs that showed no exposure of stylolites at the polished surface. In most cases, the flakes could easily be removed by means of hitting a chisel gently along the disintegrating stylolitic planes with a hammer.

b. PFM-analysis

The main conclusions drawn from the PFM-analysis, the methylene-blue test and the XRD analysis were that the stylolites in the limestone slabs contained, among others, expansive clay minerals, mainly in the form of hectorite, which belongs to the smectite or highly water-sensitive group of clay minerals. The disintegration of the slabs was attributed to a stress-controlled physical delamination of portions of the limestone slabs containing clay-rich stylolites as a result of the alternating wetting and drying of the slabs under the exposed outdoor conditions.

c. Supplementary tests

Of these four supplementary tests ('hammer test', ultrasonic pulse velocity test, Grindo Sonic test and autoclave test), only the 'hammer test' and the autoclave test were found to be suitable and reliable for assessing the quality of the slabs. The results of the other two were not suitable enough to discriminate between good and poor quality slabs. As such, they have been excluded in this article.

The 'hammer test' involved hitting various parts of the two large surfaces of the limestone slabs with a small hammer and listening to the quality of the sound that was produced. The intent of this test was to determine the occurrence of loosely bonded parts in the slabs. Slabs with weak and loosely bonded planes of stylolites yielded dull sounds similar to those produced by the disintegrating slabs containing loosely-bonded parts, which were tested in the same manner during the field inspections. This test was carried out on all the samples before and after the autoclave test.

The results of this test, which were used to classify the slabs are summarised in Tables 1 and 2 together with the results of the autoclave test.

The autoclave test is an accelerating ageing test designed to predict their long-term durability of materials (Mindess and Young 1981). In the concrete industry, the autoclave test is sometimes used as a means of curing concrete products in order to enhance certain properties of the concrete products, thereby yielding special qualities. The test can also be used to eliminate efflorescence on concretes and to reduce creep and shrinkage. With regard to quality control analysis of materials, it is believed that, defects caused by unsound constituents or deleterious impurities would reveal their effects on the quality of the material during autoclaving. This may enable the material under investigation to be rejected or accepted prior to its use (Mindess and Young 1981). It was therefore considered as a suitable method for assessing the quality of the slabs and to predict their long-term durability. The adopted hypothesis was that samples that were of the poorest quality would show the severest evidence of deterioration after the test whilst those classified as most suitable would show the least form of deterioration or preferably may no deterioration at all. This hypothesis does not take into account the existence of defects or flaws, such as internal microcracks, weak zones and planes that could not be detected visually prior to the test. In the present autoclave test, the limestone slabs were subjected to steam at high atmospheric pressures of 8 bars in a pressure vessel. The atmospheric pressure of 8 bars was achieved within 1 hour after closing the vessel. This pressure was then maintained for a period of 4 hours before releasing it. The associated temperature was about 160 °C. This was followed by visual examination of the slabs for evidence of deterioration. The deterioration or damage that had occurred, were, at the time of opening the vessel, eminent. The results of the autoclave test are presented in Tables 1 and 2. The condition or state of the slabs before and after the test is shown in Fig. 5 and 6.

For the damaged slabs, the loosely bonded flakes were easily removed from the respective slabs by means of hitting a chisel with a small hammer along the planes of satellites. Nearly all the forms of disintegration that were observed from the autoclave test were similar to the damage that was observed during the field investigation of the slabs used in the concrete elements. After removing the loosely bonded flakes containing the stylolites, the exposed surfaces of the samples were examined with the aid of a stereomicroscope. Nearly all the examined surfaces were found to contain soft, fine-grained, reddish-brown clayish material, completely different in character from the hard, sound and nearly impermeable limestone portion. Analysis of some of the soft materials by means of X-ray diffraction analysis confirmed these materials to consist among others of smectites, a group of clay minerals that are classified as highly water-sensitive.

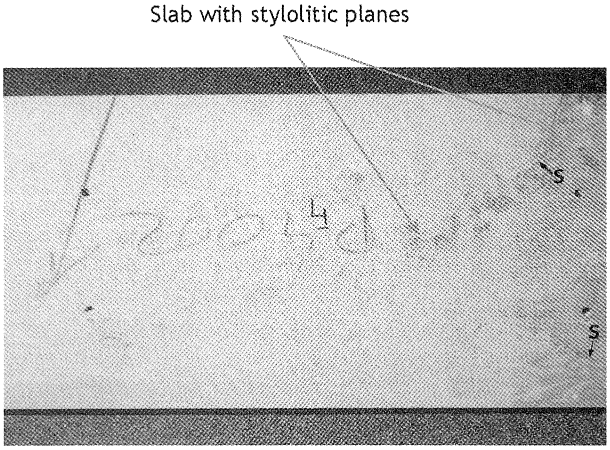

Fig. 5. Overview of a sample of the limestone slab before the autoclave test showing no visible damage. S = stylolite.

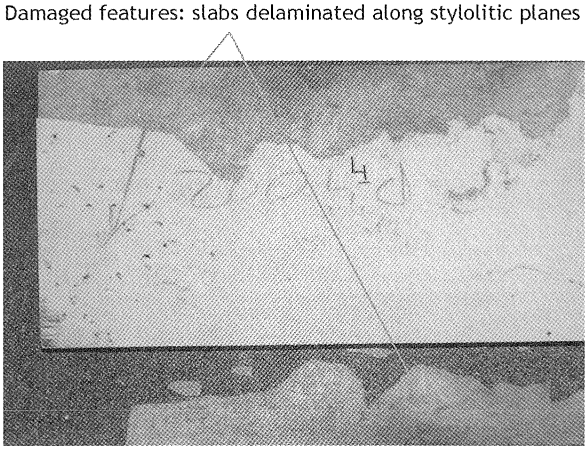

Fig. 6. Overview of a sample of the limestone slab after the autoclave test showing visible damage in the form of delamination along the inherent stylolitic planes.

3.2 *Travertine floor tiles*

3.2.1 Problem

The second case study was concerned with visible damage in the surface of slabs of travertine containing stylolites that were used as floor tiles in a house. According to the house owner, prior to the damage, the floor was cleaned two to three times a month with water containing a special detergent. These cleaning activities were done upon instructions of the contractor. Barely six months after completion of the floor and put into use, the surface of the tiles began to show various forms of deterioration, which became more pronounced after about one year. The deterioration was manifested in the form of local swelling and material loss along the stylolitic planes, development of cracks along the planes of the stylolites and formation of various surface indentations (Figs. 7 and 8).

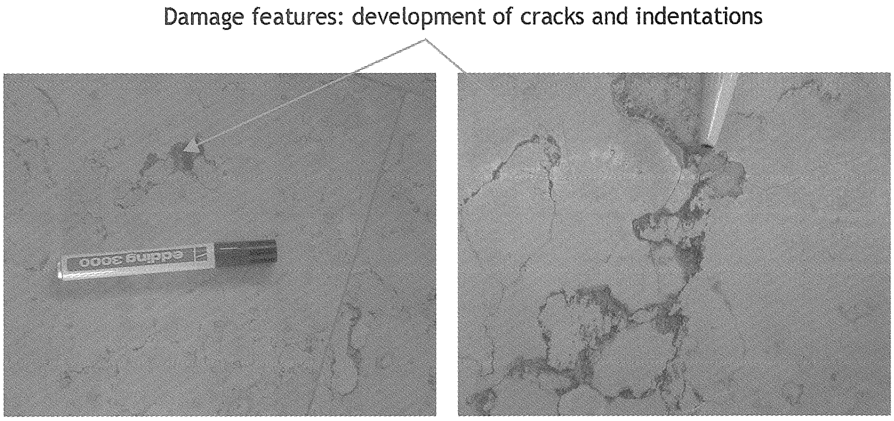

Fig. 7. Overview of part of the floor in the kitchen showing samples of the travertine tiles with various forms of damage: crack development, surface indentations and material loss.

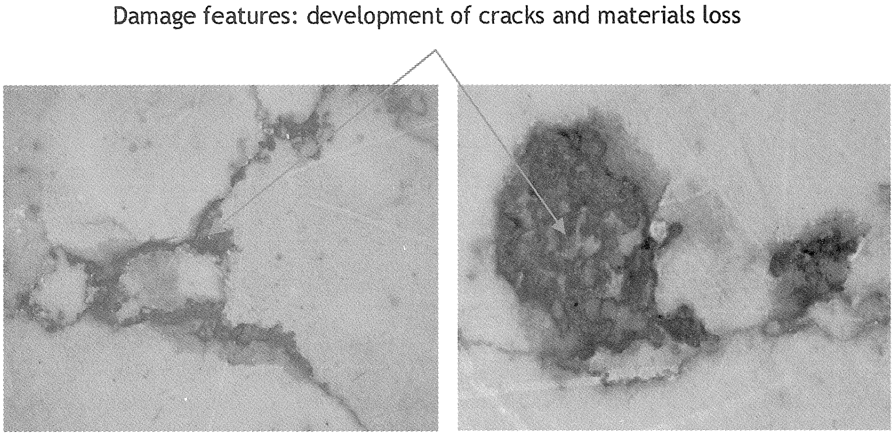

Fig. 8. Overview of part of the floor in the entrance hall and corridor showing various forms of damage in the travertine tiles: crack development and material loss in the surface.

3.2.2 *Investigation*

A site inspection of the floor was made to assess the deterioration and its extent in the tiles, and to determine the probable cause of the damage. Each tile measured of 300 x 300 x 15 mm^3. The damage appeared in the form of local cracks and material loss along the bedding plane of the stylolites and various forms of indentations or popouts in the surface (Figs. 7, 8 and 9). The distribution in the floor was found to be random, but the gravity of the damage appeared to be severest in the areas of the floor where the tiles were most intensely used. Local areas in front of the refrigerator, the washing basin and the oven that were frequently used showed the severest forms of deterioration. In general the intensity of deterioration was severest in the kitchen, followed by that in the hall, with the least occurring in the sitting room. It appeared from the observations made that the deterioration in the tiles was related primarily to the cleaning activities and to a less extent the effect of human operations in specific areas in the house.

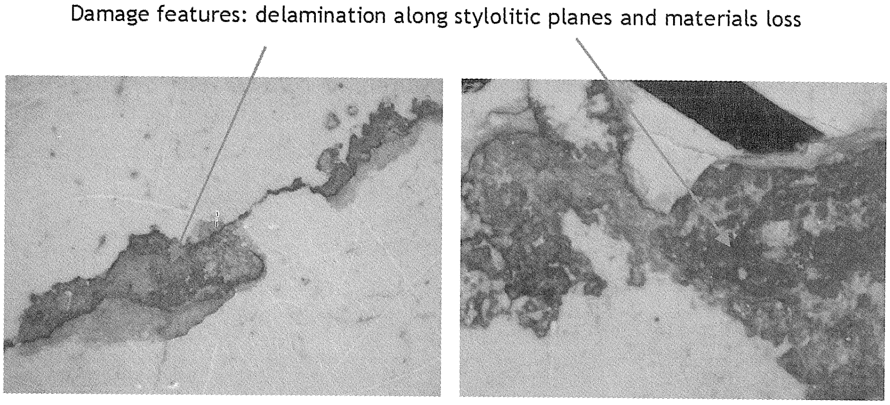

Fig. 9. Overview of part of samples of the travertine tiles removed from the kitchen showing various forms of damage: delamination along stylolitic planes and material loss in the surface.

3.2.3 *Microscopic studies*

Representative specimens, including planes of the stylolites, were taken from the tile samples removed from various parts in the room and examined with the aid of a stereomicroscope (Fig. 10). Also, fluorescent thin sections were prepared from portions of reference samples (samples that had not yet been used in the floor) and those removed from tiles showing damage, and examined by means of polarising and UV-fluorescent microscopy. In addition, some of the materials filling the planes of stylolites in the tiles showing damage were removed and subjected to X-ray diffraction analysis.

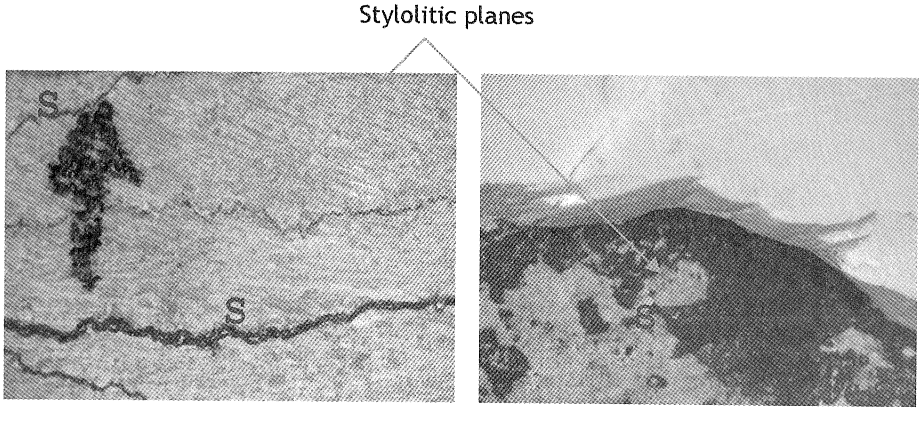

Fig. 10. Stereomicrographs of a cross-section and overview of a travertine tiles removed from the kitchen showing expanded stylolites and delamination along a stylolitic plane, S. Size of micrographs is 15 mm x 12 mm.

3.2.4 *Results PFM and XRD analyses*

The slabs of travertine were found to consist essentially of angular microcrystalline crystals of calcite and small amounts of quartz, residues of fossils, mica, clay, opaque minerals and local traces of organic inclusions cemented together by fine grains of calcite (Fig. 11). The size of the calcite crystals ranged between 0.1 and 0.5 mm and that of the quartz grains was about 0.1 mm. A number of stylolites were clearly visible in the thin sections made. They varied in width from 0.2 mm up to about 1 mm (Fig. 11). Fine crystals of carbonates (about 50 % by volume), iron oxides, giving a reddish-brown colour (about 25 % by volume), quartz (about 10 % by volume) and clay minerals (about 20 % by volume) were found in the planes of the stylolites.

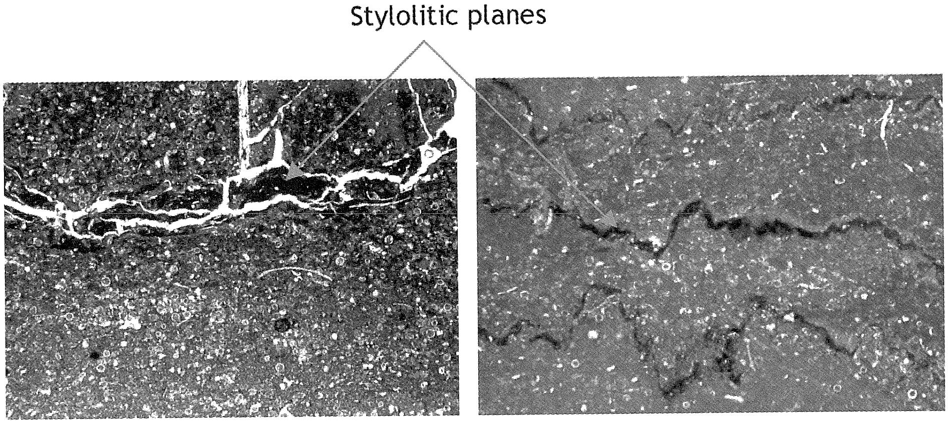

Fig. 11. PFM-micrographs of an overview of a sample of the travertine tile showing stylolitic planes containing traces of organic inclusions and oxides. Size of micrograph is 5.4 mm x 3.5 mm.

The X-ray diffraction analysis showed that the materials in the stylolitic planes were composed mainly of acid-insoluble residues of quartz and iron oxides, in addition to substantial amount of expansive clays, mainly montmorillonite, which is a highly water-sensitive clay mineral. The damage in the surface of the travertine slabs appeared to be related to the presence of the water-sensitive clay mineral in the planes of stylolites in the travertine slabs.

3.3 *Discussion of results*

In both case studies, the damage appeared to be initiated by the contact that water makes with the water-sensitive clay minerals in the stylolites. With respect to the facing slabs, visual inspection of both the damaged and undamaged slabs, supported by microscopic analysis, methylene-blue test and the XRD analysis showed that the main caused of the damage was the presence of clay-rich stylolites. This type of clay is very sensitive to water and swells considerably when it absorbs water. The disintegration of the slabs was attributed to swelling of the clay (as a result of alternating wetting and drying of the slabs under the exposed outdoor conditions) and subsequent weakening of the stylolitic planes, causing physical local delamination of portions of the slabs and further weakening of the clay-rich stylolitic planes.

With respect to the travertine slabs, the small amounts of water that gradually infiltrated the clay-rich stylolites, each time the tiles were cleaned is the cause of the deterioration. This amount of water was enough to cause the water-sensitive clays in the stylolites to swell and upon drying shrink. This process of alternating wetting and drying of the tiles, each time cleaning of the tiles occurred, caused stresses to be developed in the surface of the tiles around areas of the stylolites, which were high enough to cause surface cracking, disintegration, indentations and ultimately material loss in the surface of the tiles.

3.4 Assessment rocks containing stylolites for use in the building industry

Good quality, strong and durable rocks and stone, cut to suitable sizes, maybe use as building materials for various structural purposes such as slabs, blocks or columns and for decorative purposes such as ornaments. Although dimension stone has been used for several ages and continues

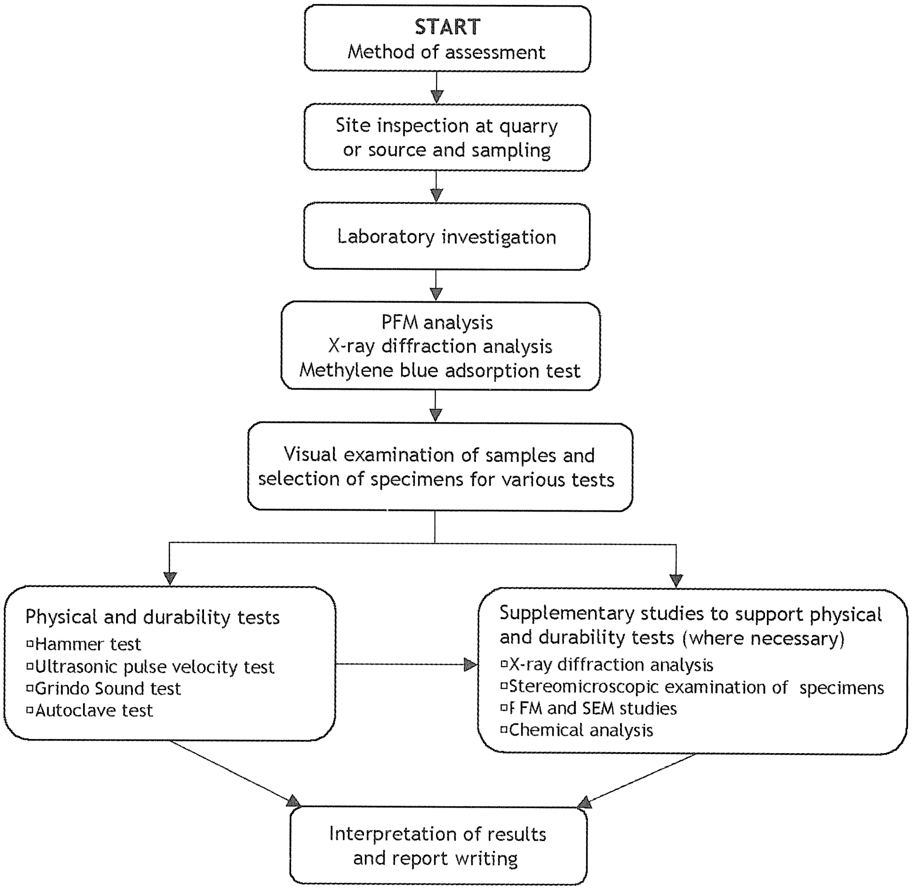

Fig. 12. Systematic approach of a proposed method for assessing the suitability of natural stones containing stylolites for use as facing, decorative or ornamental stones or as floor tiles.

to be employed for facing and other ornamental work, each time a new quarry is opened, there is the need to thoroughly assess the material prior to its use for various purposes. This is quite important especially if the rocks are suspected to contain inhomogeneities such as stylolites. This is because they can weaken the stone by allowing water to penetrate the stone and dissolve some of the constituents in the stylolites or cause them to swell, especially when they contain expansive lay minerals of the smectite group. For this reason, assessment of rocks containing stylolites for use as facing stones or floor tiles should follow a systematic manner consisting of site inspection, sampling of the (quarry) material and laboratory investigations as shown in Fig. 12.

3.4.1 Site inspection

The site inspection is aimed at identifying the beds, layers or areas of the quarry containing potentially deleterious stylolitic seams and taking of samples for the laboratory investigations. It is also intended to gather information about the quality or condition of the slabs that have already been sawn and exposed to outdoor weather conditions but not yet used in the intended construction. During the site inspection, information should be gathered from the quarry owners of structures or buildings in which such rocks have been used and their performance with regard to durability. During the inspection, a classification system can be given to the rocks examined as follows:

1 = very good : rock slab containing no visible stylolites, which may be accepted for use
2 = good : rock slab may contain only a single, thin, hardly visible stylolite, which may be accepted for use
3 = moderately good : rock slab may contain only a few, thin, hardly visible stylolites, which may be accepted for use without further testing
4 = fair : rock slab may contain a number of visible stylolites, which may or may not be accepted for use depending on the density, thickness and orientation of the stylolites in the slabs and history of performance, which may require or further testing in the laboratory in order to adequately and completely assess it
5 = poor : rock slab contains several, thick stylolites with poor history of performance, which may result in outright rejection.

During the site inspection, care should be taken to inspect the all the stylolites in a given slab, especially the occurrence of stylolites with loosely-bonded materials. Such features give indications of weaknesses in the planes of the stylolites, possibly due to the presence of expansive or excessively swelling clay minerals. A small geological hammer may be to test the quality of the sound that was produced by giving gentle taps on the surfaces of the slabs, especially along the planes of the stylolit-es. This test is usually performed in order to determine whether or not portions of the slabs especially those along the stylolites contain weak planes or are loosely bonded.

3.4.2 Laboratory investigations

The laboratory investigations may consist of a set of physical studies and durability or ageing tests. In a summary, such studies may consist of the following series of tests:

a. Hammer test

The aim of this test is usually to detect the presence of loosely bonded parts in the slabs, especi-ally those along the planes of the stylolites. The test usually involves hitting different parts of the two large surfaces of the slabs with a small hammer and then listening to the quality of the sound that is produced. Slabs with weak and loosely bonded planes of stylolites yield dull sounds similar to those produced by disintegrated slabs containing loosely bonded parts.

This test should be carried out on all the samples before and after durability or ageing tests, such as the autoclave test. The results of this test should be used in combination with other tests to classify the slabs into their various qualities.

b. The ultrasonic pulse velocity test

The ultrasonic pulse velocity test is a non-destructive test that is used in practice to detect the existence of flaws or deteriorated portions in concrete structures and other building materials. It involves sending short-period pulses of high-frequency vibrations into the material being tested and measuring the time taken for a pulse to traverse a known length of the material. From the time measurements, the velocity of the ultrasonic wave can be calculated. Using this calculated velocity, together with the density and the Poisson's ratio, the modulus of elasticity E can be evaluated for the material. The method is independent of the geometry of the material hence it is conveniently applicable to many shapes of materials. This test can be used to evaluate the quality of two slabs - a very good quality slab and a slab with a poor quality at several different points in order to select those in between these two extreme quality slabs. If the two slabs had different thicknesses across which the pulses travel, the results should be 'normalised' using the respective traversed distances. Unless the thickness of the two slabs vary considerably the test would not be able to discriminate between the qualities of the two slabs.

c. The Grindo Sonic test

This test is usually designed to investigate the quality of the slabs with regard to the existence of weak zones or planes, which are not directly exposed at the surface of rock specimens or slabs. It is similar to the ultrasonic pulse velocity test (Mindess and Young 1981), however, unlike the ultrasonic pulse velocity test, the Grindo Sonic test is related to the geometry of the material being tested and to the modulus of elasticity of the materials as well. The test involves bringing into contact a plastic cord containing a sensor at one of the diagonal ends of the slabs and giving the other end a gentle tap with a rubber stud. A form of wave is then generated throughout the slab. The resulting dissipating wave from the slab, which is dependent on the homogeneity and the extent of flaws in the slab, becomes picked up by the attached sensor at the other end of the slab. The information relating to the structure of the material from the dissipating wave becomes converted into a number called the Grindo value on a device attached to the sensor. This Grindo value, R, is related to the modulus of elasticity as follows:

$$E = [m \, . \, M \, . \, 10^3] \, / \, [b.R^2] \, (kN/mm^2)$$

where,

E = modulus of elasticity (kN/mm^2)
m = mass of the slab (g)
b = breadth of the slab (mm)
R = the Grindo value
M = a constant which depends on the length and the thickness of the slab

The Grindo Sonic test is useful for rock with large flaws but may not be able to discriminate the rocks with minor flaws and nearly homogenous structures.

d. The autoclave test

Autoclaving is an accelerated ageing test or a process of accelerating the age of materials in order to determine their long-term durability (Mindess and Young 1981). In the concrete industry, autoclaving is sometimes used as a means of curing special concrete products in order to enhance certain properties, thereby yielding special qualities. The test can also be used to elimin-ate efflores-cence on cement-based concretes and mortars and to reduce creep and shrinkage.

With regard to quality control analysis of materials, it is believed in general that, defects caused by unsound materials or deleterious impurities in the materials to be tested would reveal their effects on the quality of the materials during autoclaving. This may enable the materials to be rejected or accepted prior to their use (Mindess and Young 1981). Details of the test are already given in paragraph. The usual adopted hypothesis is that samples with the poorest quality would show the severest evidence of deterioration or degradation after the test and those the highest quality would show the least form of deterioration or preferably may not deteriorate at all. This hypothesis does not usually take into account the existence of defects or flaws such as intrinsic microcracks, weak zones and planes that could not be detected visually prior to the test.

4 Concluding remarks

Inhomogeneities, such as stylolites, when they occur in natural building stones may have profound effect on their mineralogy and internal structure, which subsequently can influence to a large extent their durability. With the naked eye not all stylolites an their inherent constituents may be detected, which may cause such building stones to be inaccurately classified as dense, homogenous and impermeable. The present studies, which makes use of an integrated method, consisting of traditional physical and durability tests, combined with optical microscopy and X-ray diffraction analysis shows that on the microlevel, such inherent inhomogeneities can be detected and their nature (mineralogical composition and internal structure) characterised. The information gathered from such integrated method, especially the microscopic studies may be used to assist in the quality control analysis of new building stones or for making diagnosis of the type and the extent of deterioration in already used ones. The integrated method, based primarily on optical microscopy used in all phases of these investigations has proved to be an excellent tool for characterising the stones and the stylolites present.

When used by qualified personnel, it can play a key role in the diagnosis of the causes of deterioration of the natural building stones and for evaluating the various treatment or remedial measures applied to the stones.

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