Bending strength properties of untreated and impregnated igneous, sedimentary and metamorphic dimension stones of different thickness

T. SAHLIN[1], J. STIGH[1] & B. SCHOUENBORG[2]

[1] *Göteborg University, Earth Sciences Centre; Geology, PO Box 460, SE-405 30 Göteborg, Sweden (e-mail: torgny@gvc.gu.se)*

[2] *SP, Swedish National Testing and Research Institute, PO Box 857, SE-501 15 Borås, Sweden*

Abstract: A production method has been developed that makes it possible to produce dimension stone tiles only 4 mm thick without high amounts of waste material. The tiles are impregnated with a mixture of potassium-based water-glass, water, colloidal silica, and Berol 048 (non-ionic surfactant), using a repeated cycling between vacuum and atmospheric pressure. Mineralogy, fabric, and porosity affect the mechanical properties of rock used as dimension stone in the building industry. Tests for bending strength have been performed on tiles of eight different untreated and impregnated samples of igneous, sedimentary, and metamorphic rocks. Samples of three different thicknesses (4, 7 and 10 mm) were used in the tests. The untreated rock samples that had a fine-grained texture, low crack density, high mafic mineral content or a distinct ductile metamorphic texture showed the highest bending strength values, whereas those that had high amounts of carbonate minerals, and high crack or void density exhibited the lowest values. The stone types that gained the most from impregnation, in general, were those with high crack or void density.

A production method has been developed that makes it possible to produce dimension stone tiles only 4 mm thick without high amounts of waste material. The tiles are impregnated with a mixture of potassium-based water-glass, water, colloidal silica, and Berol 048 (non-ionic surfactant), using a repeated cycling between vacuum and atmospheric pressure. There is no difference in colour or lustre between untreated and impregnated stone. Conventional dimension stone tiles used as building material are normally untreated and are at least 10 mm thick. The purpose of the impregnation treatment is to increase the mechanical strength and durability of stone tiles and to allow production of more tiles from a raw block by making thinner tiles. This is an advantage not only economically but also environmentally. In addition, the product is easier to handle due to its reduced weight.

Rocks differ in physical and chemical properties, depending on mineralogy, grain size, grain shape, porosity, and water content. The mechanical properties are important when using rocks as building materials. This study concerns bending strength, a crucial mechanical property when using dimension stones for flooring and outdoor cladding.

A test programme was set up in order to investigate differences in bending strength properties between impregnated and untreated stone material. The tests for bending strength were performed on eight different rocks under both impregnated and untreated conditions, and with three different sample thicknesses. Altogether four igneous (two granites, one larvikite, and one dolerite), two sedimentary (one sandstone and one limestone), and two metamorphic (one gneiss and one marble) rocks were chosen. The studied rocks exhibit large variations in mineralogical compositions, and in chemical and physical properties.

Previous work and scientific studies have been performed concerning treatment, conservation, consolidation, and to a lesser extent impregnation of already existing buildings, sculptures, and monuments totally or partly made up of stone material. However, most of the earlier investigations have been concentrated on sandstones, limestones, and marbles since these rocks are not as resistant to weathering as crystalline rocks such as granites, and they are the rock types most frequently used in old buildings and cultural artefacts, and the research in general has focused on historic preservation.

Rocks analysed

Eight rock types of different origin and with a wide range in physical and chemical properties

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Table 1. *Rock types with geological name, international trade name and name in this study used*

Rock type	Geological name	International trade name	Name used in this study
Granite	Växjö granite	Tranås Red	Tranås granite
Granite	Iddefjord granite	Iddefjord Monolith Grey	Iddefjord granite
Syenite to monzonite	Larvikite	Blue Pearl	Blue Pearl larvikite
Dolerite	Manyika-type noritic dolerite	Nero Zimbabwe	Nero Zimbabwe dolerite
Sandstone	Dala sandstone	Älvdal Quartzite	Dala sandstone
Limestone	Holen/Segerstad limestones	Jämtland Limestone	Jämtland limestone
Gneiss	Migmatitic gneiss	Barents Red	Barents gneiss
Marble	Dolomitic marble	Snow White of Thassos	Thassos marble

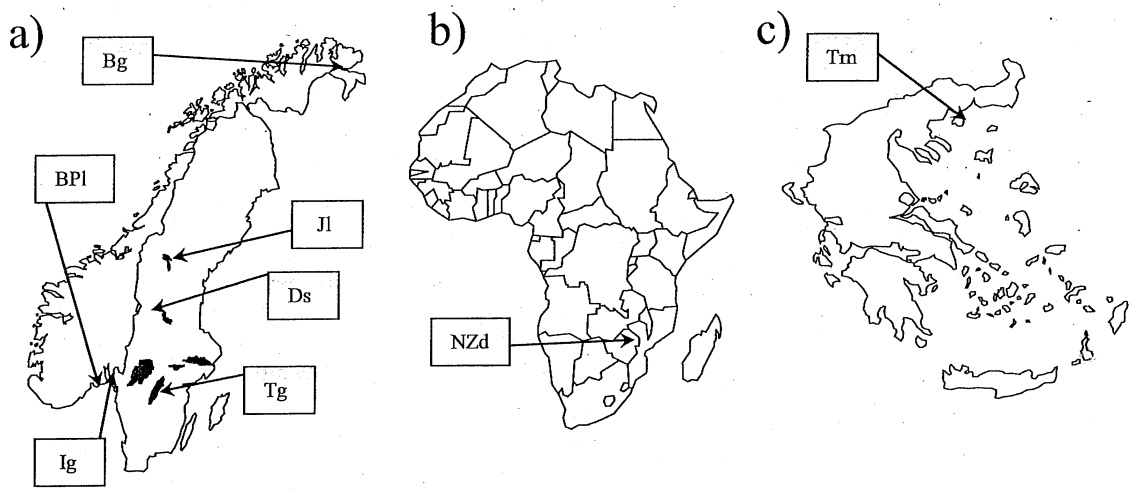

Fig. 1. Geographic localities of the studied rocks. (**a**) Norway and Sweden: Tranås granite (Tg), Iddefjord granite (Ig), Blue Pearl larvikite (BPl), Dala sandstone (Ds), Jämtland limestone (Jl), and Barents gneiss (Bg). (**b**) Africa: Nero Zimbabwe dolerite (NZd). (**c**) Greece: Thassos marble (Tm).

have been studied (Table 1). The geographic localities of the investigated rocks are shown in Figure 1. Mineralogical and textural analyses were performed using untreated rock samples. For determination of the mode of each rock type used, modal analysis was carried out on thin sections using a polarizing microscope.

Tranås granite

The Tranås granite is a variety of the Proterozoic Växjö granite (e.g. Persson *et al.* 1985; Jarl & Johansson 1988) quarried at Kungshult, approximately 7 km NNW of Tranås, Småland, southern Sweden (Fig. 1). The Tranås granite is produced in one quarry only and the annual production is about 600 m^3 (A. Janiak, pers. comm. 2000). Both raw blocks and finished products are produced for export and domestic use.

In hand specimen the Tranås granite displays pale, bluish-grey 5–10 mm quartz grains, 10–15 mm red feldspars, dispersed subordinate green epidote, and some dark minerals. Microcracks are randomly orientated. The texture is coarse-grained, phaneritic, and inequigranular. In thin section (Fig. 2a) the granite consists of undulose quartz (*c.* 40 vol%), slightly perthitic microcline (*c.* 40 vol%), sericitized plagioclase (*c.* 15 vol%), and minor biotite, chlorite, epidote, sphene, zircon, and opaque minerals. The quartz grains occur either as large deformation domains or as

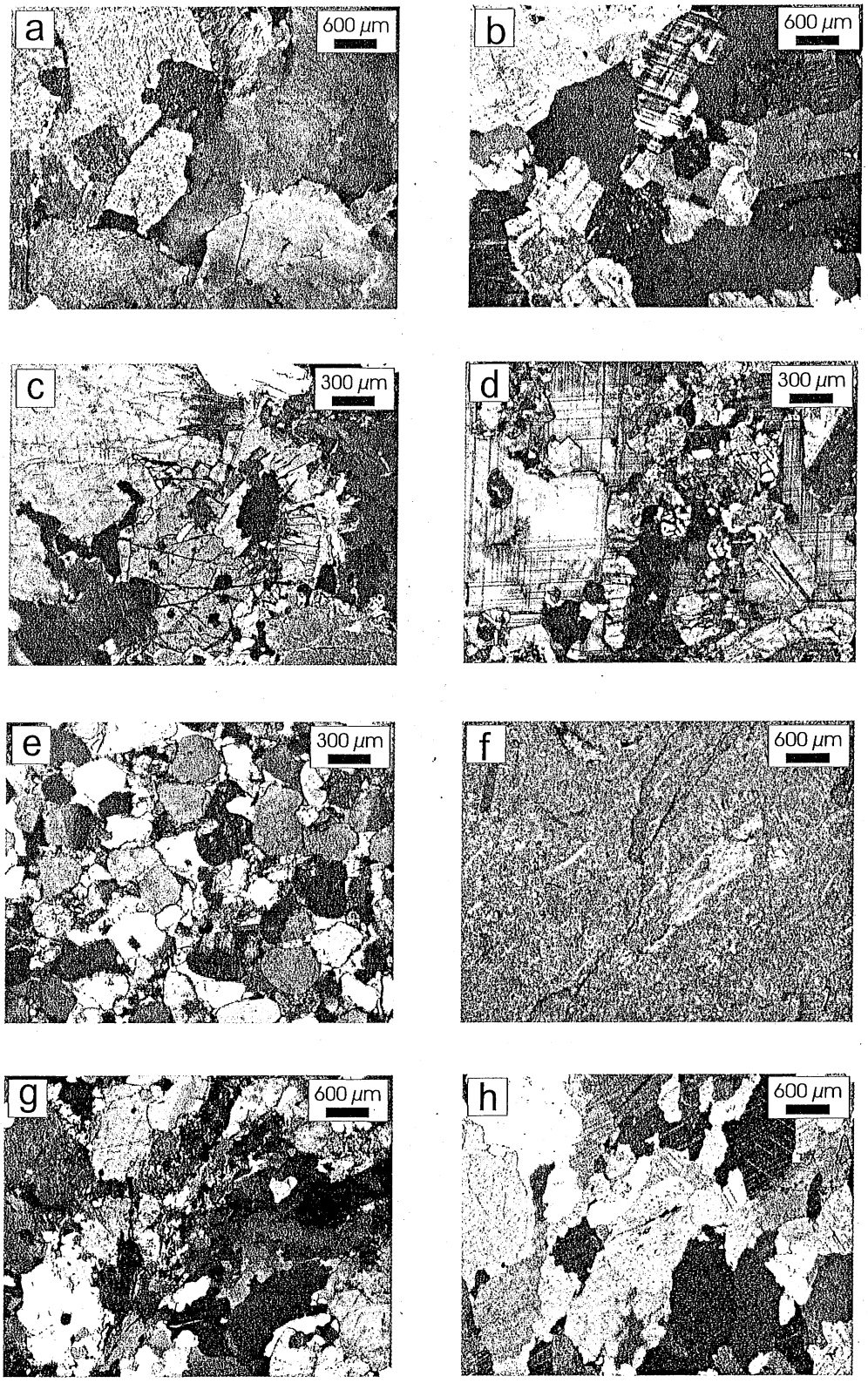

Fig. 2. Microscopic images of the analysed rock samples; polarized light with crossed polars. (**a**) Tranås granite. (**b**) Iddefjord granite. (**c**) Blue Pearl larvikite. (**d**) Nero Zimbabwe dolerite. (**e**) Dala sandstone. (**f**) Jämtland limestone. (**g**) Barents gneiss. (**h**) Thassos marble.

subgrains mixed with epidote. In the microcracks within larger mineral grains, epidote and some of the biotite grains are chloritized.

Iddefjord granite

The international trade name of the grey variety of the Neoproterozoic Norwegian Iddefjord granite is Iddefjord Monolith Grey or simply Iddefjord. This granite is quarried south of Halden, Østfold, south-eastern Norway (Fig. 1). Both raw blocks and processed products are produced for export and domestic use. Reusch (1891) first described the quarrying operations for this rock.

The Iddefjord granite belongs to the Bohus-Iddefjord batholith, which occurs in Sweden and Norway. The batholith is a composite granitic massif formed by multiple magma pulses (Eliasson 1992). Usually the granite is grey or reddish grey, but bluish grey varieties do occur (Pedersen & Maaløe 1990). In general, the granite is evenly grained, but slightly porphyric varieties do exist. The main minerals are plagioclase, microcline, and quartz. The accessory minerals are biotite, hornblende, muscovite, Fe-oxides, chlorite, apatite, sphene, and zircon.

In hand specimen the Iddefjord granite used in this study displays a phaneritic, inequigranular, and coarsely medium-grained texture. The quartz grains are grey and 1–2 mm, the feldspars primarily are grey and 1–10 mm, and the dark mineral grains are about 1 mm. In thin section (Fig. 2b), the granite is composed of strained, undulose quartz (*c.* 30 vol%), microcline with tartan twinning (*c.* 30 vol%), and plagioclase (*c.* 30 vol%). The accessory minerals are biotite (ordinary and chloritized varieties), chlorite, epidote, euhedral allanite, and some opaque minerals. The feldspars are in general poikilitic, enclosing chlorite and biotite. Quartz and feldspar show high microcrack density.

Blue Pearl larvikite

Permian larvikite, first described by Brøgger in 1890, is one of the most commonly used dimension stones in the world. It is produced from approximately 20 quarries in the Larvik district, Vestfold, southern Norway (Berthelsen & Sundvoll 1996) (Fig. 1). Raw blocks of a value corresponding to more than 47 million Euros are exported annually. Depending on qualitative characteristics such as colour, brightness, and lustre, the larvikite is divided into two different international trade names: Blue Pearl and Emerald Pearl. The Blue Pearl is more expensive and well known, showing a bluish, deep, intense, pearly lustre.

According to Brøgger (1890), the larvikite is a variety of augite syenite to monzonite consisting of rhomb-shaped ternary feldspars (with a distinctive schiller texture), barkevikite (Fe-rich hornblende), Ti-augite, and lepidomelane (Fe-rich biotite). Minor nepheline, Fe-rich olivine or quartz may be present. Different varieties of larvikite are to be found in the Larvik district (Berthelsen *et al.* 1996).

The coarse-grained, phaneritic, and inequigranular Blue Pearl larvikite consists almost entirely of feldspar grains, up to 3 cm of various shapes, with subordinate dark minerals. Most of the feldspar grains exhibit a moonstone schiller texture, which is due to an intimate cryptoperthitic lamellar intergrowth, and are microcracked. The variation in end-member composition, anorthite (Ca), albite (Na), and orthoclase (K), in the feldspar of larvikite is $An_{7-15}Ab_{61-67}Or_{8-32}$ (Engvoldsen 1991). In thin section (Fig. 2c), the Blue Pearl larvikite consists of cryptoperthitic feldspar (*c.* 90 vol%) and minor clinopyroxene, barkevikite, biotite, lepidomelane, Fe-rich olivine, augite, quartz or nepheline, sphene, and opaque minerals.

Nero Zimbabwe dolerite

The Proterozoic Nero Zimbabwe dolerite is quarried in northeastern Zimbabwe (Fig. 1). 'Black granite' is the common international trade name for a dark grey to black dolerite (microgabbro or diabase) used for monumental and decorative purposes (Barton *et al.* 1991). The main source of 'black granite' is in north-eastern Zimbabwe in the Mutoko region. 'Black granite' of Zimbabwe has the international trade name Nero Zimbabwe, although some other names occur. This dolerite has been quarried from a number of places since the early 1970s from within a large, gently inclined sill between 50 and 100 m thick (Barton *et al.* 1991; Roberts 1992). Nero Zimbabwe is produced and exported mainly as raw blocks.

The Nero Zimbabwe belongs to the Manyika-type noritic dolerite (Barton *et al.* 1991) and is composed of almost equal amounts of pyroxene and plagioclase. The best quality is almost black in colour and has an even medium-grained texture. The plagioclase grains are cloudy due to the presence of numerous minute needle-like inclusions. These inclusions may affect the internal reflectivity of the plagioclase grains, enhancing the dark appearance of the polished stone (Barton *et al.* 1991; Roberts 1992). Some parts of the sill show concentrations of plagio-

clase grains and this phenomenon reduces the 'production quality' and hence the trade value of the rock.

In hand specimen the Nero Zimbabwe dolerite is greyish black, and the plagioclase is characterized by a silver-metallic lustre. The texture is fine- to medium-grained, subophitic, and aphanitic. In thin section (Fig. 2d), the essential minerals are plagioclase (*c.* 35 vol%), clinopyroxene (*c.* 30 vol%), orthopyroxene (*c.* 10 vol%), and a myrmekitic quartzo-alkali-feldspatic residue (*c.* 10 vol%). The accessory minerals consist of quartz, biotite, hornblende, and magnetite. Plagioclase is between 0.25 and 5 mm and is generally poikilitic, enclosing both pyroxenes. The orthopyroxene shows a weak pleochroism and occurs mainly as euhedral (*c.* 3 mm), lath-shaped grains. It also occurs as smaller intergranular grains. The clinopyroxene appear as large (*c.* 5 mm) lath-shaped grains and also as small (*c.* 1 mm) intergranular grains or intergrown aggregates often associated with the myrmekite. Fracture-infills of fine-grained alteration material (biotite and hornblende) are typical. The magnetite exhibits both euhedral and skeletal grains.

Dala sandstone

The Middle Proterozoic Dala sandstone clastic sequence is about 800 m thick and occupies an area of more than 6000 km^2 in west-central Sweden and adjacent parts of Norway (Lindström *et al.* 1991; Pulvertaft 1985). The sandstone is used as a dimension stone, and is produced from only one quarry in Mångsbodarna, the county of Dalarna, central Sweden (Fig. 1). The international trade name is Älvdal Quartzite. Both raw blocks and processed products are produced for export and domestic use. Annual production, in terms of raw blocks, is approximately 1500 m^3 (R. Eriksson, pers. comm. 2000).

The mineralogical composition of the ruddy and fine-grained Dala sandstone comprises the detrital components quartz (*c.* 70 vol%), feldspar (*c.* 15 vol%), and rock fragments (*c.* 10 vol%). The most common diagenetic minerals are quartz, illite, chlorite, hematite, titanium minerals, calcite, and feldspar (Hjelmqvist 1966; AlDahan 1985). The sandstone displays a quartzitic microcrystalline character and the grains are well rounded (Fig. 2e). The matrix consists of quartz.

In thin section (Fig. 2e), the Dala sandstone used in this study shows major undulose quartz, alkali feldspar with tartan twinning, sericitized plagioclase and minor calcite, hematite, and allanite. Hematite occurs between the quartz and the feldspar grains. The major minerals display a saccharoidal texture.

Jämtland limestone

The Jämtland Limestone, which is the common trade name for the Ordovician Holen and Segerstad limestones, is produced in a few quarries situated in the Östersund area in the county of Jämtland, central Sweden (Fig. 1). This limestone has been quarried since the twelfth century. Main products for export and domestic use are wall and floor casings, staircases, and window seats. Limestones of different colours, mainly brownish red and grey, are quarried and processed.

The Jämtland limestone used in this study is brownish red in colour and contains mainly calcite (*c.* 80 vol%), some quartz (*c.* 10 vol%), and hematite, which gives the brownish red colour (Karis & Strömberg 1998). In hand specimen most of the grains cannot be identified, except hematite fracture-infills and dispersed quartz blebs approximately 5 mm in length. In general, the limestone shows high crack density. In thin section (Fig. 2f), the Jämtland limestone contains calcite, some quartz and hematite. Quartz and hematite occur as fracture-infills. The texture is microcrystalline.

Barents gneiss

The reddish and migmatitic Barents gneiss is quarried in the area of Grasbakken in Nesseby, Finnmark, northern Norway (Fig. 1) and its international trade name is Barents Red. A bluish-grey variety, which is named Barents Blue, is quarried in Bugøynes approximately 25 km east of Grasbakken. The total resources of these dimension stones are estimated to be 1.3 $\times$ 10^6 m^3 (E. Lund, pers. comm. 2000) and are produced for export and domestic use as raw blocks and processed products.

The Barents gneiss belongs to the Archean Varanger Gneiss Complex and is characterized by red and dark diffuse banding, which is parallel, folded, and in some cases very irregular. It is generally medium-grained with granoblastic texture. The origin of some of the banded units is not certain although most lithologies are probably of igneous derivation (Dobrzhinetskaya *et al.* 1995). The metamorphic grade corresponds to amphibolite facies.

In thin section (Fig. 2g), the Barents gneiss consists of quartz (*c.* 40 vol%), plagioclase (*c.* 15 vol%), microcline (*c.* 30 vol%), biotite

(*c.* 15 vol%), and minor apatite. The microcline is perthitic and exhibits tartan twinning. Biotite constitutes the planar fabric and some of the grains are chloritized.

Thassos marble

In Greece, nearly 3500 marble producers and manufacturers employed more than 50 000 people in 1995. The most exploited area is Drama–Kavala–Thassos in the northeastern part of the country where more than 100 000 m^3 of white and greyish-white marble is produced and processed for export each year. Marble from the Thassos island (Fig. 1) has been quarried since the seventh century BC and is used in sculptures and buildings all over the world. The dolomitic Thassos marble used in this study is quarried in the northeastern part of the island and is known as Snow White of Thassos.

In hand specimen the Thassos marble is characterized by an extremely bright colour. The texture is fine-grained and saccharoidal. The marble has been dolomitized and dedolomitized periodically (Waelkens *et al.* 1988). Due to these processes voids have been formed. The marble consists of 86 wt% dolomite, 12 wt% calcite, and 2 wt% quartz (Alexandri 1991). However, no quartz has been found in the Thassos marble used in this study. In thin section (Fig. 2h), dolomite and calcite exhibit a bimodal grain size distribution. Larger grains are approximately 1.3 mm and the smaller ones are about 0.2 mm. Deformational twinning as well as sutured to curved planar grain boundaries occur. The texture is a combination of inequigranular, decussate (interlocking grains), and xenotopic (anhedral grains).

Impregnation chemical

The impregnation chemical is composed of four components: potassium-based water-glass, water, colloidal silica, and Berol 048 (Table 2).

Potassium-based water-glass, also called potassium silica (SiO_2/K_2O), has a mole ratio within the range 0–4. The ratio of the water-glass used is 3.3 (trade qualities are usually 2.0–3.5). The viscosity of water-glass in general (including sodium-based water-glass) is between 10 and 1000 mPa s. However, it varies with temperature, especially within the range 0–60°C. An increase in the temperature will cause a significant drop in viscosity. pH is generally within the range 11–13.5 (trade quality). The density is generally between 1100 and 1650 kg m^{-3}.

Colloidal silica, or silica sol (SiO_2/Na_2O), has a mole ratio of approximately 100 and consists of 10–50 nm silica particles homogeneously dispersed in water. The silica sol used in this study has been developed by Eka Chemicals, Sweden. The trade name is Bindzil®30/220 with a particle size of 15 nm, a pH of 9.7 and a viscosity of less than 7 mPa s.

Berol 048, developed by Akzo Nobel Surface Chemistry, Sweden, is a non-ionic surfactant based on tridecyl alcohol. It has a hydrophilic character. The density at 20°C is 1020 kg m^{-3}. The viscosity at the same temperature is 140 mPa s. Berol 048 is used as a wetting agent during the impregnation process and 0.786 g is added per litre of impregnation solution.

Methods

Production of thin stone tiles

Rock slabs about 16 mm thick were cut from raw blocks using diamond cut-off wheels and flushing water. A vacuum chamber connected to a vacuum pump via an autoclave was used for the slabs intended to be impregnated. The pump was connected for 20 minutes at a pressure of approximately −1 bar, allowing moisture and dirt to escape from the crack and pore systems within the slabs. Inside the chamber, the slabs were treated with the impregnation chemical using a repeated cycling between vacuum and atmospheric pressure. After the impregnation

Table 2. *Components of the impregnation chemical*

Components	Density (kg m^{-3})*	Concentration (wt%)
Potassium-based water-glass	1200	64.6
Water	1000	8.5
Colloidal silica	1200	26.9
Berol 048	1020	+

*After the hardening/dehydration process the density of the impregnation chemical is approximately 2100 kg m^{-3}.
+0.786 g is added per litre of impregnation solution.

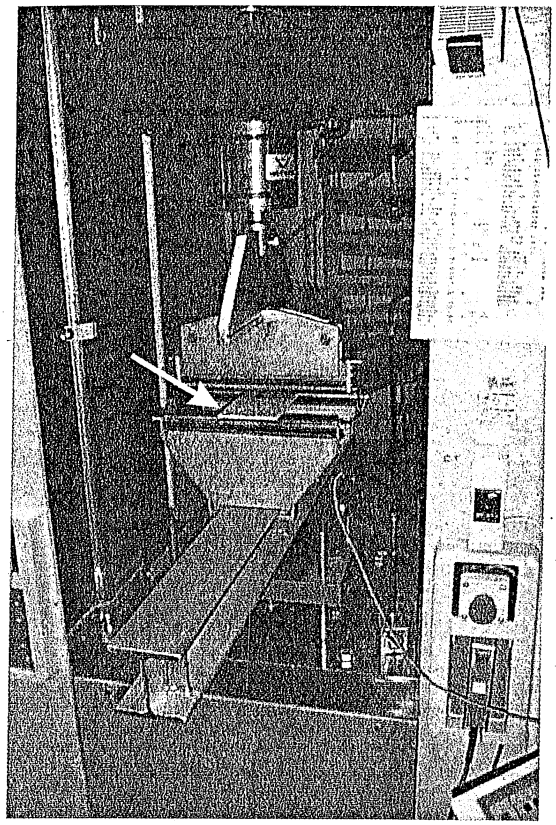

Fig. 3. The Instron 1253/8500 testing machine. The arrow points at a rock sample situated between the knife-edges.

process, the slabs were dried with infrared heating. The impregnated slabs were then further processed to their final thickness (4, 7 or 10 mm).

The rocks used are considered to be isotropic, except the Dala sandstone where the anisotropy, which is weak, is due to diagenesis. Since the rocks do not show preferred mineral orientations due to deformation all sample slabs were cut randomly from the raw block material. The samples (including those intended to be impregnated) were then mixed before further processing.

Bending strength tests

The bending strength tests were performed on impregnated as well as untreated samples. Prior to the tests, the impregnated samples were dried at 70°C for three days. The reason for this was to ensure that the impregnation chemical was completely dried and dehydrated before performing the tests. Five samples of each series of impregnated and untreated rocks were used.

The bending strength was measured according to DIN 52112-A on dry samples by use of an Instron 1253/8500 testing machine with a load cell capacity of 10 kN (Fig. 3). Rectangular prisms 200 × 100 mm in size were used. These were placed on two supporting knife-edges in a three-point load setup (Fig. 3). The sample thicknesses were 4, 7 and 10 mm, in order to be able to correlate the results of the impregnated samples with the corresponding thickness of the untreated ones. The samples were 'calibrated' on both surfaces but honed on the upper surface only. Calibration is used here in the same way as in the natural stone industry, i.e. a final control and finishing to the required dimension tolerances. The applied load rates were 1.18 N s^{-1} for the 4 mm thick samples, 3.63 N s^{-1} for the 7 mm samples, and 7.41 N s^{-1} for the 10 mm ones. The diameter of the supporting knife-edges, situated underneath and perpendicular to the length direction of a sample, was 20 mm. The span length between these supporting knife-edges was 180 mm. The loading knife-edge, situated above a sample, was placed at the centre of the span, parallel to the supporting knife-edges.

Results

The bending strength results are presented according to a subdivision into igneous, sedimentary, and metamorphic rock samples. The relationships between the impregnated and the untreated rock samples, irrespective of thickness, are shown in Figures 4 and 5.

Igneous rocks

The untreated Nero Zimbabwe dolerite showed the highest strength, independent of thickness in relation to the other untreated rocks studied. The untreated Iddefjord granite had the lowest strength.

For the impregnated samples, the dolerite maintained its high strength values. However, the Tranås granite showed both higher and lower strength values for the various thicknesses. The most marked improvement was in the Iddefjord granite. For example, the 4 mm impregnated samples were twice as strong as their untreated counterparts.

Similarly to the Iddefjord granite, the impregnated Blue Pearl larvikite displayed higher strength values than the corresponding untreated samples.

The impregnated 4 and 10 mm Nero Zimbabwe dolerite showed higher strength values relative to the untreated specimens of 4 and 10 mm thickness, respectively. However, the impregnated 7 mm samples showed lower strength than the 7 mm untreated ones.

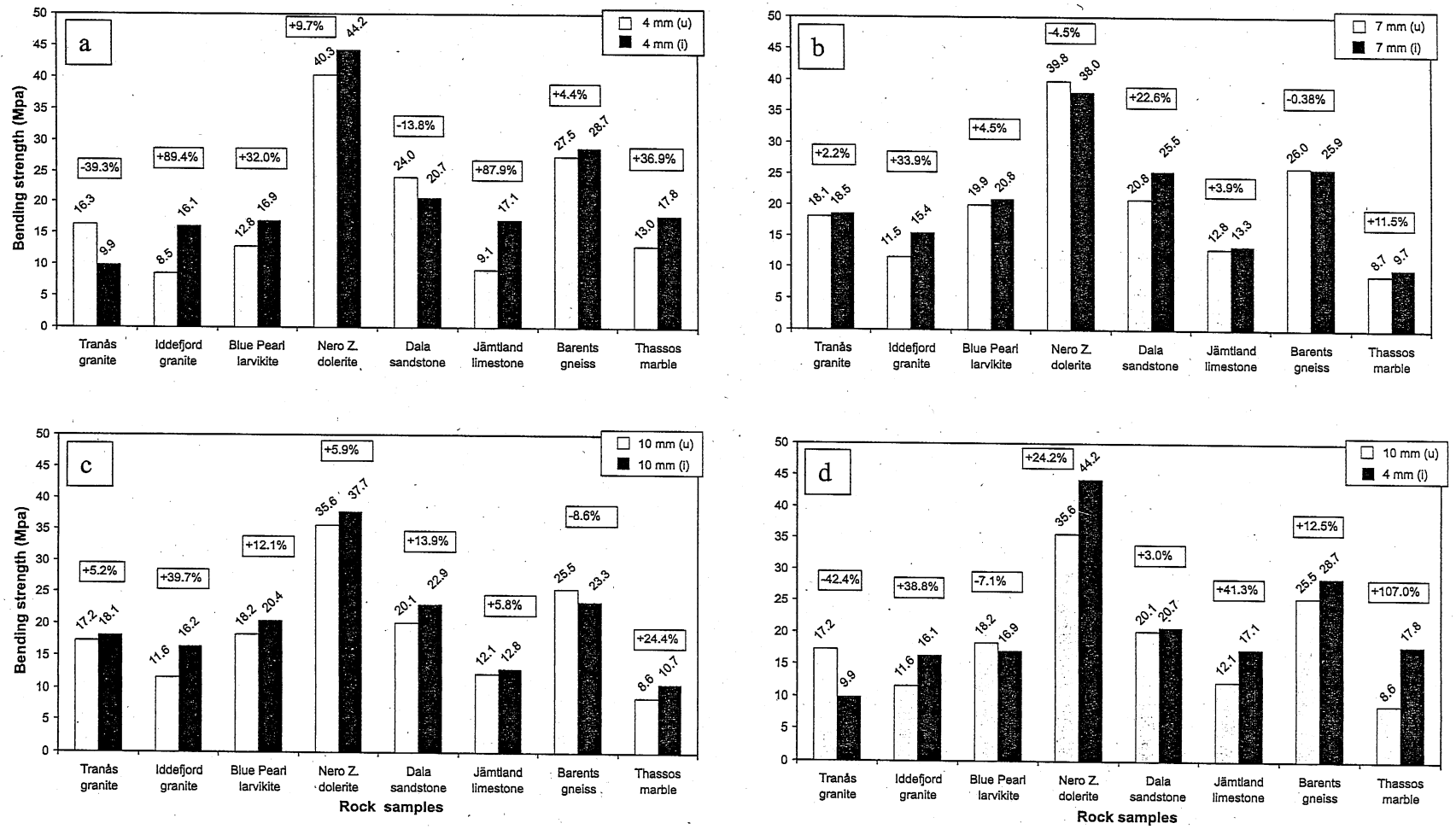

Fig. 4. Bending strength mean values of untreated (u) and impregnated (i) rock samples of different thickness. The value on top of each bar is the mean value of each sample series. The percentages correspond to the difference in strength between untreated and impregnated samples of each rock type of specific thickness. (**a**) 4 mm samples. (**b**) 7 mm samples. (**c**) 10 mm samples. (**d**) 10 mm untreated versus 4 mm impregnated samples.

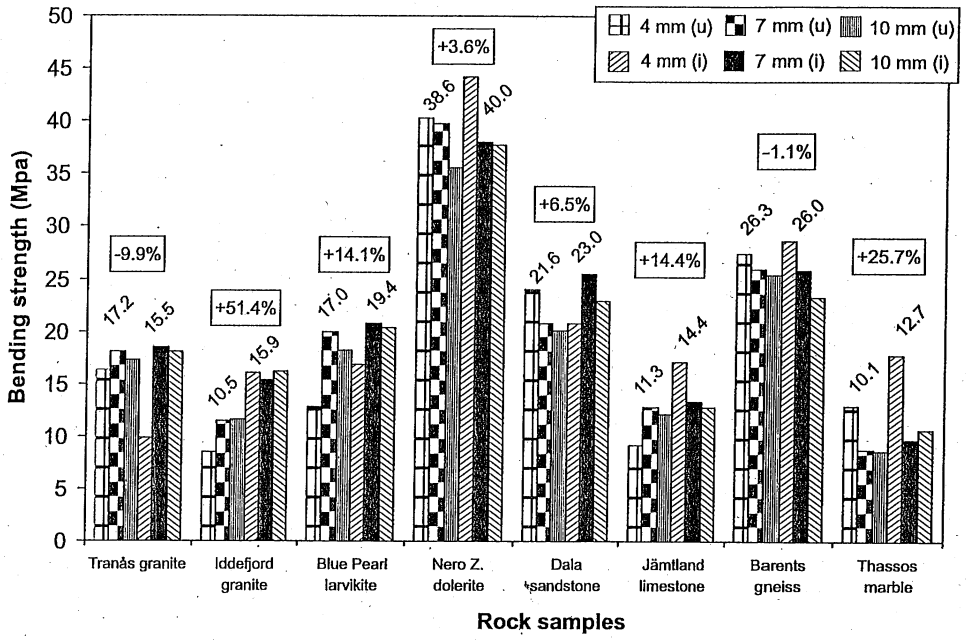

Fig. 5. Compilation of bending strength mean values of all untreated (u) and impregnated (i) samples. The values on top of bars correspond to the mean values of each 4, 7 and 10 mm untreated and impregnated sample series respectively. The percentages correspond to the difference in strength, taking into account all thicknesses, between untreated and impregnated samples of each rock type.

Sedimentary rocks

The Dala sandstone showed higher strength values than the Jämtland limestone, irrespective of thickness and impregnation.

The 7 and the 10 mm impregnated Dala sandstone showed higher strength than corresponding untreated samples of the same thickness. In contrast, the inverse relationship was shown for the 4 mm samples. A slightly higher strength was obtained for the 4 mm impregnated samples compared to the 10 mm untreated ones.

A much higher strength (almost 90%) was shown for the 4 mm impregnated Jämtland limestone compared to the 4 mm untreated samples, whereas only a slightly higher strength was shown for the 7 and 10 mm impregnated samples compared to the corresponding untreated samples. Higher strength was shown for the 4 mm impregnated samples compared to the 10 mm untreated ones.

Metamorphic rocks

The Barents gneiss showed higher strength values than the Thassos marble independent of thickness and impregnation.

Higher strength values were obtained for the 4 mm impregnated Barents gneiss compared to the corresponding untreated 4 and 10 mm samples. Approximately no strength difference was shown between the impregnated and the untreated 7 mm samples. Regarding the 10 mm impregnated versus the 10 mm untreated samples, the impregnated ones showed lower strength. When comparing each thickness separately, irrespectively of thickness, the impregnated Thassos marble showed higher strength compared to the untreated ones. The strength of the 4 mm impregnated samples was more than twice as high compared to the 10 mm untreated samples.

Coefficient of variation

For each sample series, coefficients of variations (CVs) have been calculated from the individual strength values and their corresponding means and standard deviations (Table 3). CVs can be used when comparing the spread of the observations in different sample series and hence information can be obtained about the heterogeneity of a rock. The CV is defined by:

$$CV = \frac{100 \times S}{\overline{X}}$$

where S is the standard deviation and $\overline{X}$ is the mean value of a sample series.

Discussion

Mineral composition, grain size, grain shape, porosity, permeability, and water content are important factors that affect the physical properties of rock materials. The spatial distribution and the density of these factors can influence the rock in such a way that it will show different physical properties in different directions (anisotropy). These differences are controlled by mineral orientation and distribution, grain size distribution, foliation/stratification, and orientation and distribution of fractures or pore systems. Hence, the size and shape (scale factor) of a sample is important in this context, especially for heterogeneous and anisotropic rocks. This means that the dimension of the test specimen in relation to the setup of the strength machine (distance between supporting knife-edges) is an important influencing parameter.

According to Onodera & Asoka Kumara (1980), the mechanical properties of a rock depend upon its genetic texture including mineral composition and microcracks. Compressive strength and tensile strength show a linear increase with decreasing grain size or increasing grain boundary surface area per unit volume. In general, microcrack dimensions are comparable with grain size. The coarser the grain size the longer and wider are the existing microcracks. Tensile strength increases with decreasing grain size and crack density. Whereas compressive strength does not vary much with decreasing grain size, tensile strength is remarkably higher in the finer grained rocks.

Bending strength is a combination of compressive and tensile strength. During a bending strength test, the forces acting on a sample correspond to a combination of compressive and tensile stresses.

Untreated material

Bending strength mean values based on the three different thicknesses of each rock can be viewed in Figure 5. In this section the untreated rock samples, without considering specific thickness, are discussed in relation to bending strength properties of the rock types, their mineralogy, and fabric, including microcracks.

The granites (Tranås and Iddefjord) show similar mineral composition. The even-grained Tranås granite displays coarser grains but lower microcrack density than the inequigranular Iddefjord granite. The Tranås granite showed higher strengths compared to the Iddefjord granite, which most likely is primarily due to the microcrack density. Mafic (Fe-Mg rich) minerals are less fragile/brittle than felsic minerals. Fracture infills of epidote and biotite in microcracked larger quartz and feldspar grains are common in the Tranås granite, which could be related to the higher strengths. This type of infill cannot be recognized in the Iddefjord granite.

The Nero Zimbabwe dolerite showed the highest strengths. This may be due to its fine-grained texture and generally low crack density in combination with its mafic mineral content (e.g. the high pyroxene content).

The Blue Pearl larvikite showed intermediate bending strength values. This could be due to the fact that the less fragile mafic minerals are situated in between the more fragile microcracked and large-sized feldspar grains.

The Dala sandstone has a higher strength compared to the Jämtland limestone, the Thassos marble, and the igneous rocks except for the dolerite. The rather high strength values obtained by the sandstone may be due to the fine-grained mineral grains and well-cemented matrix.

The Jämtland limestone exhibited low strengths, which may be due to the fact that carbonate minerals are fragile, in combination with the high crack density.

The Barents gneiss showed high strengths; only the Nero Zimbabwe dolerite showed higher values. Gneiss is in general a heterogeneous and anisotropic rock. However, the Barents gneiss did not show high CVs (Table 3). On the other hand, this rock shows a distinct ductile metamorphic texture, almost of anatectic character, which may affect the strength.

The Thassos marble showed low strength values, probably because carbonate minerals are fragile in combination with the presence of voids.

Bending strength and thickness dependence

Bending strength is dependent on sample size including its thickness. A thicker sample may contain larger defects, affecting its strength ('thickness defect risk', TDR). However, if a sample shows larger (or equal) grain size than the corresponding thickness of the sample, the grains are distributed in such a way that no supporting surrounding grains exist in the 'third dimension' ('no supporting grains in the third dimension', NSG). For such samples, the bending strength may be lower compared to samples of the same thickness showing smaller grain size distributed in three dimensions.

The highest bending strength values for the Tranås granite and the Blue Pearl larvikite was obtained for the 7 mm samples. The lower value

Table 3. Bending strength mean values, standard deviations, and CVs for the untreated (u) and the impregnated (i) rock sample series of different thickness

Rock name	Sample series	Mean value (MPa)	Standard deviation	Coefficient of variation (%)
Tranås granite	4 mm u	16.3	1.5	8.9
	4 mm i	9.9	2.8	28.6
	7 mm u	18.1	1.6	9.1
	7 mm i	18.5	0.6	3.0
	10 mm u	17.2	1.4	8.1
	10 mm i	18.1	0.9	4.9
Iddefjord granite	4 mm u	8.5	0.9	10.2
	4 mm i	16.1	0.4	2.2
	7 mm u	11.5	0.3	2.3
	7 mm i	15.4	1.3	8.4
	10 mm u	11.6	0.5	4.5
	10 mm i	16.2	0.5	3.1
Blue Pearl larvikite	4 mm u	12.8	4,1	32.1
	4 mm i	16.9	1.7	10.1
	7 mm u	19.9	1.0	5.0
	7 mm i	20.8	0.7	3.1
	10 mm u	18.2	0.4	2.3
	10 mm i	20.4	1.5	7.5
Nero Zimbabwe dolerite	4 mm u	40.3	3.5	8.7
	4 mm i	44.2	2.5	5.6
	7 mm u	39.8	2.6	6.5
	7 mm i	38.0	1.3	3.5
	10 mm u	35.6	3.6	10.1
	10 mm i	37.7	1.2	3.1
Dala sandstone	4 mm u	24.0	3.9	16.2
	4 mm i	20.7	1.6	7.9
	7 mm u	20.8	2.6	12.5
	7 mm i	25.5	1.6	6.3
	10 mm u	20.1	1.1	5.7
	10 mm i	22.9	2.7	11.8
Jämtland limestone	4 mm u	9.1	2.6	28.7
	4 mm i	17.1	4.9	28.4
	7 mm u	12.8	6.1	47.5
	7 mm i	13.3	3.5	26.0
	10 mm u	12.1	1.6	13.5
	10 mm i	12.8	1.7	13.4
Barents gneiss	4 mm u	27.5	1.2	4.3
	4 mm i	28.7	0.8	2.7
	7 mm u	26.0	0.9	3.5
	7 mm i	25.9	3.7	14.2
	10 mm u	25.5	0.8	3.2
	10 mm i	23.3	2.6	11.2
Thassos marble	4 mm u	13.0	0.6	4.9
	4 mm i	17.8	1.5	8.3
	7 mm u	8.7	0.2	2.5
	7 mm i	9.7	0.5	5.5
	10 mm u	8.6	0.2	2.1
	10 mm i	10.7	0.5	4.7

obtained for the 4 mm samples could be due to the NSG effect, since these rocks are coarse-grained, whereas the lower values for the 10 mm samples could be due to the TDR effect since these two rocks display high density of microcracks.

The 4 mm samples of the Iddefjord granite exhibited the lowest strength. The somewhat stronger 7 and 10 mm samples showed the same values. The lowest value obtained for the 4 mm samples could be due to the NSG effect. The feldspar grains show various sizes (1–10 mm). There is no TDR effect. This could be due to the high microcrack density in the quartz and

feldspar grains that may impair the bending strength even in the thinnest samples.

The highest strength for the Nero Zimbabwe dolerite was obtained for the 4 and 7 mm samples. This could be due to the fact that this rock is very fine-grained and hence did not display any NSG effect for these thin samples. The lower strength for the 10 mm samples could be due to the TDR effect.

The Dala sandstone and the Barents gneiss showed the same thickness trends. The 4 mm samples showed the highest strength followed by the 7 mm ones, and finally the 10 mm ones. For the Dala sandstone this phenomenon could be due to the rock's fine-grained texture and hence there was no NSG effect for the 4 mm samples. The bending strength values for the 4 mm Barents gneiss cannot be explained by the NSG effect since this rock is in general coarse-grained. On the other hand, the gneiss shows a distinct ductile metamorphic texture, which may give strength in two dimensions. The strength of the 7 and 10 mm samples may be due to the TDR effect.

The Jämtland limestone exhibited the same thickness dependence trends as the Tranås granite and the Blue Pearl larvikite. However, the strength results for the 4 mm samples cannot be explained by the NSG effect since this rock is very fine-grained. The limestone exhibited very high coefficients of variations (Table 3), and hence the results from the different thicknesses are hard to interpret.

The 4 mm Thassos marble showed the highest strength values. The values obtained from the 7 and 10 mm samples were approximately the same. The high bending strength result obtained from the 4 mm samples could be due to the absence of the NSG effect since the marble is fine-grained. The Thassos marble exhibits voids, which could be related to the lower strengths for the 7 and 10 mm samples due to the TDR effect.

Impregnated versus untreated material

Not all impregnated rock types showed improved bending strength compared to the corresponding untreated samples. The values vary not only depending on rock type, but also depending on thickness.

It is believed that the impregnation chemical used in this study covers the surface of the impregnated rock samples with a thin layer. However, its penetration ability, penetration depth and transport paths during impregnation are a subject for future investigations. Interpreting the bending strength test results, in general, regarding the different impregnated rock samples (of different thickness) in relation to untreated samples is complicated. The following points are important to bear in mind. (1) The influence of the impregnation process, i.e. the vacuum treatment and stresses induced during penetration of the chemical and stresses induced during the drying process before testing, has not been studied. (2) The dehydration/contraction effect of the impregnation chemical may be smaller in a sample's interior due to less contact with air compared to near-surface areas. (3) The adhesiveness of the impregnation chemical on mineral grains may differ depending on the grains' chemical and physical properties and in turn may differ between different rock types. (4) The size of cracks and/or pore systems may affect not only the penetration depth of the impregnation chemical, but also what the dehydrated products' network will look like. This in turn may influence at least the mechanical properties of impregnated materials. (5) Depending on mineralogy, chemical reactions may take place between certain minerals and the impregnation chemical, which could change the physical properties of impregnated materials. (6) The stability of the impregnation chemical in time (durability).

The impregnated 4 mm Tranås granite showed much lower bending strength compared to corresponding untreated samples. On the other hand the 7 and 10 mm samples exhibited a slight strength improvement for the impregnated samples. This phenomenon could be due to the Tranås granite being sensitive to the impregnation process and further to the processing afterwards (sawing, calibration, polishing). Existing microcracks may be longer and wider and maybe even new cracks will be developed during the processing. The 4 mm samples may then be more sensitive during the further processing than the 7 and 10 mm ones.

The Dala sandstone showed the same trend as the Tranås granite. The difference between the 4 mm samples was not as high as for the granite, whereas the bending strength improvement for the impregnated 7 and 10 mm sandstone samples was slightly higher. This could be due to the fact that the sandstone is also sensitive to microcrack propagation during processing but not as much as the Tranås granite.

Irrespectively of thickness, the impregnated Iddefjord granite, Blue Pearl larvikite, Jämtland limestone, and Thassos marble showed higher strength values compared to corresponding untreated samples. The greatest difference was obtained for the 4 mm samples. This means that these rocks are not sensitive to the processing.

The Iddefjord granite showed the greatest differences between impregnated and corresponding untreated material. This is most likely primarily due to the high microcrack density, which may have a three-dimensional perpendicular network that might act as penetration paths for the impregnation chemical. In addition, the Bohus-Iddefjord granite (Asklund 1947) has a distinctive fracture system with three fracture sets perpendicular to each other. It has been used as a source for paving stone production due to this well developed fracture pattern.

The impregnated 4 and 10 mm Nero Zimbabwe dolerite showed slightly higher strength than the untreated counterparts. On the other hand, the impregnated 7 mm dolerite showed slightly lower bending strength in relation to the corresponding untreated samples. However, even if the dolerite is quite homogeneous compared to the other rocks studied, this phenomenon could be due to heterogeneity differences between sample series (see CVs in Table 3). For example, the impregnated 7 mm sample series could have a somewhat different mineralogy and texture, and may display higher microcrack density than the other series.

The impregnated 4 mm Barents gneiss showed slightly higher strength compared to corresponding untreated samples. No difference in strength was observed between the impregnated and untreated 7 mm samples. The impregnated 10 mm samples displayed slightly lower strength than the 10 mm untreated ones, which could be due to heterogeneity differences between sample series (Table 3).

Conclusions

Of the untreated rocks, the Nero Zimbabwe dolerite showed the highest bending strength values compared to the other rocks studied, due to its fine-grained texture, normally low crack density, and high mafic mineral content. The Barents gneiss showed the second highest strength, probably due to its distinct ductile metamorphic texture. The Jämtland limestone and the Thassos marble exhibited the lowest values, most likely because these rocks have high amounts of carbonate minerals, and high density of cracks and voids, respectively. The Tranås granite showed higher strength values than the Iddefjord granite, and this is probably due to differences in microcrack density and the mafic mineral content.

When comparing the strength differences between impregnated rocks versus their untreated counterparts, we conclude that the Nero Zimbabwe dolerite does not improve with impregnation. This is probably due to a low penetration ability of the impregnation chemical, which in turn is due to the dolerite's fine-grained texture and in general low crack density. The Tranås granite is likewise not suitable for impregnation for production of 4 mm tiles. For production of 7 or 10 mm tiles there is no need for impregnation. This phenomenon may be due to sensitivity to the impregnation process and further processing, where microcrack propagation may take place, especially regarding production of 4 mm tiles. The Thassos marble, the Jämtland limestone, and in particular the Iddefjord granite are the most suitable rocks for impregnation. This is most likely primarily due to the void content for the marble and the high microcrack density for the limestone and the granite that may act as penetration paths for the impregnation chemical.

The geological factor that seems to have most effect on the bending strength properties examined in this study is the fabric of the rock and not the mineralogy (cf. Åkesson *et al.* 2001). However, a relationship also exists between bending strength properties and mafic mineral content.

In order to obtain the highest quality of thin untreated dimension stone products regarding bending strength properties, rocks should have a fine-grained texture, low crack or void density, high mafic mineral content or a distinct ductile metamorphic texture. Rock types that display the highest strength improvement due to impregnation are those with high crack or void density.

For the production of very thin (e.g. 4 mm) and fragile dimension stones, there must not be a high bending strength difference between impregnated and untreated material. During the cutting and sawing processes less waste material will in general be produced for impregnated material.

For an understanding of how the impregnation process differs between rock types, further studies have to be performed on the impregnation chemical itself regarding its penetration ability, adhesiveness, dehydration/contraction properties, potential chemical reactions with minerals, and durability/ageing factors. Different impregnation chemicals with varying physical and chemical properties may have to be developed for rock types with different physical and/or chemical properties. Moreover, different impregnation techniques may have to be developed for rocks with different properties. More fragile rocks should

not be subjected to such high pressure differences and/or so many pressure cycles during the impregnation operation as the less fragile rocks.

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