Use of natural stone and stone construction

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In his book *Oikeat ja väärät arkkitehdit* ('Right and wrong architects') architect Timo Penttilä, referring to Jan Assmann's book *The Mind of Egypt*, talks about how stone was a material of sacral construction in Egyptian architecture while clay bricks dried by the sun belonged to the profane. Stone was associated with the holy, immovable and eternal time, while clay was associated with the secular, movable and transient time. (Penttilä 2003.)

Natural stone is used in construction in many ways both in buildings and environmental construction. In buildings, natural stone is used in facades and as decorative stone (floors, furniture). Restoration targets, such as castles, fortifications and stone churches make up a significant share of the natural stone construction volume.

The durability of natural stone structures is affected not only by the stone material used but also by the structural solutions and other materials used in the structures, such as the sealant. The climatic conditions of the construction site also have a great effect on the durability of the structures.

This handbook is aimed at designers, developers and stone industry using stone. There are existing good guidelines for designing and implementing natural stone structures, so this text will not repeat these guidelines. Neither are structural engineering, dimensioning and strength assessments of stone structures discussed; the focus is on the uses of stone in the future. Architectonical style considerations related to stone are also only discussed in passing when they are related to stone technology.

Within the framework of perspectives highlighted by our project, the text discusses natural stone as a construction product as well as natural stone solutions. From extensive possible uses of stone, we have excluded furniture, interior walls and soapstone fireplaces and concentrated in particular on buildings, their facades and floors, exterior walls and environmental stone structures.

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History and uses of stone construction in Finland

The majority of medieval Finnish natural stone structures were churches and castles. The majority of these were built between the 13th century and the beginning of the 16th century. The construction of various fortification systems continued long into the 1800s, especially in south-eastern Finland. Estates have been built out of stone since the 15th century, although some of the stone estates have been built in later centuries. Subsequent to great town fires, town houses have been built out of stone since the 18th century. Building of urban residential buildings out of stone became more common from the 19th century onwards.

Viipuri Castle (Paajanen, 2014.)

Natural stone has been used both as a loadbearing structures as non-loadbearing facing stone either in the form of a thing facade masonry of facade board supported by bearers. It is also possible to attach natural stone to, for example, concrete elements. Nowadays, the majority of natural stone facades are implemented with thin stone panels which are supported by metal brackets on the facade of the building (a notch for the brackets has been cut on the edge of the panels), which ensures good ventilation space behind the stone panels.

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 (Paajanen, 2014.)

Various hybrid structures are also very common; these include using, for example, bricks, concrete or steel in the structures in addition to natural stone.

Stone structures used in castles and churches were various grey-stone walls. It was typical of grey-stone structures that the surroundings of door and window openings were laid in bricks. Grey-stone structures can be divided in three groups according to their method of construction:

- mortar-free dry stone wall
- rammed-earth wall, which was commonly used in church and castle construction
- ashlar wall, also known as rusticated wall, became more common in Finland in the 19th century when estate and urban construction increased.

Kyminlinna Fortress in Kotka (Paajanen 2013.)

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The wall masonry of medieval churches used 'keystone masonry', where lime mortar was pushed between the stones. The stones form a loadbearing structure and support each other, while the purpose of the mortar is mainly to fill extra holes and cover the surface of the wall to prevent water from penetrating the wall and forming water pockets. (Holopainen and Helama 2012, 3.)

In environmental construction, stone has traditionally been used as a surface material for streets and squares, in various wall and support structures and sculptures. Stone has also been used in park construction and water structures such as piers, jetties, channels and bridges. In recent decades, gabion structure has become more common in supporting terrain in environmental construction. A gabion wall is constructed by filling baskets made of steel mesh with stones.

Future changes in conditions, climate change and their effect on stone structures

The effects of the climate change in in future conditions should be taken into account in particular when discussing facades and other external structures and look at circumstantial factors and their effects through this perspective.

The Finnish Meteorological Institute has prepared scenarios on the climate change and its effects in the Finnish climate. According to them, the average temperature in Finland will change 2– 6 °C warmer in the last decades of the current century than during the comparison period 1971–2000. At the same time, rain volume will increase. Based on the greenhouse scenarios, the future climate type of Finland will resemble the current conditions in Central Europe. This means that in the future structures will face great climate stress deviating from the current situation. (Vinha et al. 2013, 34.)

From the perspective of construction-physical operation of structures, the following issues related to circumstantial factors of the climate play a key role (these factors vary according to the geographical location of the building and the cardinal point):

- temperature
- relative humidity
- wind (speed and direction of wind)
- rain (amount of rain, direction and speed of wind)
- radiation of the Sun (direct, diffuse radiation, cloudiness)
- thermal radiation to the sky (sky's effective temperature, cloudiness). (Vinha et al. 2013, 67.)

In addition to the abovementioned external circumstantial factors, the microclimate, the external conditions close to the structures, are affected by various factors related to the location and shape of the building:

- the height of the location of the building
- the size, shape and height of the building
- protective structures (sheet metal cladding, eaves, grids)

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- details and structure of the external surfaces of structures (projections, hollows, characteristics of the surface)
- immediate surroundings (other buildings, tree stand and vegetation, terrain shapes, water areas). (Vinha et al. 2013, 68.)

The climate change is expected to increase the number of rainy days especially in winter, whereas in summer their number may decrease. It is expected that wind speeds and the relative humidity of outside air will increase particularly in winter. These changes will affect the operation of the dampproofing of the outer envelope of the building, for example, in the following ways:

- load of wind-driven rain on facade surfaces increases
- favourable conditions for condensation of damp and growth of mould increase particularly in the exterior parts of structures
- transfer of damp from the outside in increases particularly in facades, which absorb rain water, during summer condensation and moulding risk increases in these structures also close to the interior surface
- the drying ability of the structures weakens and slows down as dry weather spells shorten and cloudiness increases. (Vinha et al. 2013, 69.)

According to climate change scenarios, changes in outside weather conditions will not occur evenly; instead they will occur in winter and late-autumn. Even currently, autumn is the most problematic season with regard to the functioning of dampproofing technology, so the changes occurring during this season will have particularly considerable effect on the structures. (Vinha et al. 2013, 70.)

Deterioration classification


(Paajanen, 2014.)

In 2010, the ICOMOS International Scientific Committee for Stone (ISCS) of the (International Council of Monuments and Sites (ICOMOS) published an illustrated an Illustrated glossary on stone deterioration patterns. Before this, various publications of stone deterioration classifications had existed. With its publication, the ISCS has aimed at creating shared glossary. (ICOMOS 2010, 1, 4.)

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General terms when classifying stone deterioration are:

- alteration: modification of the material that does not necessary imply a worsening of its characteristics from the point of view of use of the stone
- damage: human perception of the loss of value due to decay of the stone
- decay: any chemical or physical modification of the intrinsic stone properties leading to a loss of value or to the impairment of use
- degradation: decline in condition, quality, or functional capacity.
- deterioration: process of making or becoming worse or lower in quality, value, character, etc.
- weathering: any chemical or mechanical process by which stones exposed to the weather undergo changes in character and deteriorate. (ICOMOS 2010, 8 – 9.)

The ISCS classification divides deterioration in five main classes:

- crack & deformation
- detachment
- features induced by material loss
- discoloration & deposit
- biological colonization.

Each main class is further divided in various subclasses. (ICOMOS 2010, 6.)

Different deterioration is typical of different stone types, in other words some deterioration type is detected on some stone but not at all on some other stone.

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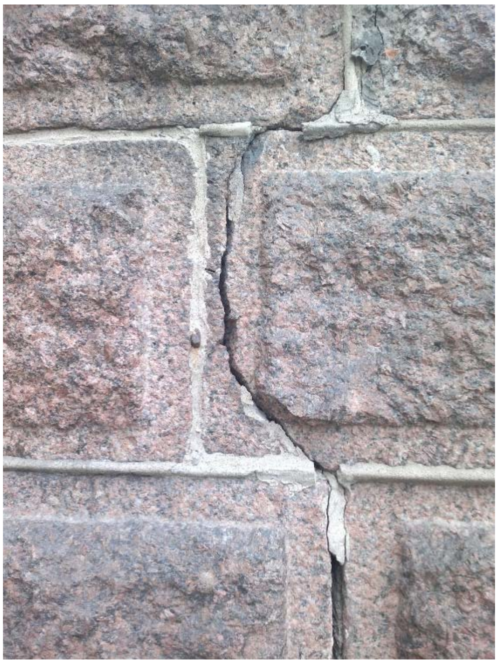
(Paajanen, 2014.)

Cracks are clearly visible to the naked eye, but they may be small hair cracks, various crack networks or major fractures. Cracks may also be caused by, for example, rusting iron supporting structure within the stone. Deformation includes various forms of bending or twisting of the stone, which is typical of marble structures. (ICOMOS 2010, 10 -15.)


(Paajanen, 2014.)

Detachment includes various instances of detachment of the outer layer of the stone, local crater-like detachments caused by internal pressure, detachment due to the layered structure of the stone, detachment of single grains and various types of detachment even large-scale detachment caused by

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external pressure. Detachment may be caused by salts, water and different mechanical strains. (ICOMOS 2010, 14 – 27.)


(Paajanen, 2014.)

Material loss may be caused by, for example, erosion and various mechanical damages. For example, a wrong kind of sealant may cause detachment in stone. Erosion can be caused by various chemical, physical or biological processes. Damage caused by erosion is typical of various types of sandstone. Mechanical damage is to a very large degree caused by people either by impact or by simply wearing down the stone (for example, on floors and thresholds). One group belonging to this class is "missing part", in other words clearly missing parts of structures, sculptures, etc. which they have possessed earlier (for example, an arm broken off from a statue). (ICOMOS 2010, 28 – 41.)


(Paajanen, 2014.)

Discoloration & deposit may include exogenic deposits of colour or discoloration of the stone's own colour, hue of the colour or colour chroma. Exogenic discoloration is encountered particularly much in urban environments on surfaces that are not rinsed clean by rainwater. Air pollution also causes discoloration of the surface. Especially salts, corrosion of metals, fungi and other bacteria as well as fires may cause discoloration. This group also includes various measures or phenomena creating a thin film on the surface of the stone (for example, graffiti protection) or (inadvertent or deliberate) polishing of the stone surface (for example, people leaning on a stone parapet and thus causing the polishing effect). Human-made graffiti are also classified to belong to this group. (ICOMOS 2010, 42 – 63.)



(Paajanen, 2014.)

Biological colonisation includes phenomena caused by plants growing on stone but also bacteria, fungi and other corresponding sources. Detrimental effects caused by these vary from changes to external appearance to detachment caused by larger plants. (ICOMOS 2010, 64 – 75.)

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Some of the degrees of the deterioration classification are damage to appearance, some larger or smaller damage to the functioning of stones or stone structures or even load-bearing capacity. The classification helps in various repair situations to determine and record unambiguously the detected detrimental issues and damage, so that they can be reacted to with appropriate measures.

Factors affecting stones and stone structures

Stone structures outside are under a great variety of influences. Often various burdens affect the stone simultaneously increasing the load. Damages caused by various burdens can be prevented with pre-planned solutions. In renovation and restoration, the causes of the damage must be determined in order to be able to select right repair methods.

Stone structures and uses of stone in construction can be roughly divided in two main groups: solid stone structures and curtain or layered structures.


(Paajanen, 2013.)

Solid stone structures are based on the use of thick, heavy and massive stones often piled on top or next to each other. The stones may be attached together, seamed or not seamed, bonded or not bonded. In solid stone structures, the shape and surface treatment of the stones may be reasonably free. With regard to structural engineering, the stone structures are supported by their foundations or foundation soil and withstand compression. Structural-physical behaviour of solid stone structures is clear and uncomplicated. As a rule, solid stone structures can only be used in cold and external structures due to their thermal conductivity.

Solid stone structures are mainly used in landscape, environmental and park construction as well as construction of traffic areas. Consequently, solid stone structures are often exposed to heavy wear caused by traffic. mechanical loads, the climate, temperatures, humidity and seawater.

 (Paajanen, 2013.)

Curtain or layered structures are based on use of thinner and smaller stones, often stone panels in layered structures. In this case, the stone panels are a separate structural layer, or a "weather wall" of the structure, often a curtain wall structure with ventilation opening. The stone panels will be attached with various mounting methods to the actual main structure bearing the load. As a rule, the mounting takes place with metal fixtures and mortar/glue mounting based on various systems. The seams of the stone panels are finished with elastic sealing compound. Consequently, curtain stone cladding is used in different circumstances than solid stone walls and the temperature and humidity conditions on the external and internal surfaces of the stone slab vary.

Curtain stone structure or ventilated curtain structure are mainly used in construction engineering in foundation walls and facades of buildings. As a rule, curtain stone structures have to endure unavoidable circumstances based on environmental stress and temperature changes as well as various loads.

Due to their different uses building stones have to withstand different conditions, which means that you should know the characteristics and use alternatives of different types of building stone. Various stone tests have been conducted in conjunction with our project (Luodes et al. 2014). The following entries regarding strain on stone structures refer mostly to the outcomes of these tests. On the one hand, the tests were limited to hard rock, and, on the other hand, to solid stone structures (Luodes et al. 2014).

Dust landing on the surface of stone and changes in mineral composition, for example oxidisation of iron, have been found in tests to cause long-term changes, in particular. Dust causes blackening of the stone, while salt deposits cause white traces. Soapstone has been found to have changed its colour from grey to brown. Dust affects soft stone, such as limestone and marble, more strongly than hard rock. In some cases, roughening of the stone surface has been detected. (Luodes et al. 2014.)

External strain and consequent colour changes may also be caused to stone by deficiently or badly designed structural details, for example, when copper or other materials run off from the roof or other sheet metal cladding.

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Mechanical strains

People cause various kinds of mechanical strain on stone structures through their actions. With regard to environmental stone these include traffic and snow removal. A big problem in Finland is strain generated by traffic. This includes mechanical wear by tyre studs and movement due to deceleration and acceleration of vehicles.

Strain directed at facade cladding includes wind load and the dead load of stone cladding. Facades of buildings are damaged particularly at ground level by various mechanical measures, collisions and impacts. When moving about and working, people cause wear on thresholds and inside floors.

Movement of the building foundations cases damage to stone structures; stone breaks when its foundation moves, since it is not elastic. Too tough sealant causes damages. Wrong choice of sealant may cause the entry of water into the structures, which means that it will cause damage inside the structure when it, for example, freezes.

Biological strain


(Paajanen, 2014.)

Biological strain includes various bacteria, fungi, algae, lichen, moss and plants all the way up to trees.

Constant humidity and favourable growth conditions, for example contact with ground or a humid shady corner, cause manifestation of biological strain on the surface of stones, for example, growth of moss. This in turn causes accumulation of heavy metal, which has strain consequences of its own. Vegetation typically causes a high moisture ration. Vegetation may cause detrimental effects with regard to external appearance but also detachment of stone. Various rock types are susceptible to biological strain, particularly to lichen and algae, with sandstone being more sensitive than hard granite. Higher vegetation is found on all platforms. Different microclimate conditions greatly affect the occurrence of biological strain. For example, studies have found great differences in the occurrence of various types of lichen in various circumstances. On the other hand, lichen work well as an air quality indicator, since they do not thrive in polluted air. (Luodes et al. 2014.)

When calculating the effects of the climate change, the future climate of Finland can be compared with the current climate in Central Europe. This means that biological strain will increase in Finland in the future.

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Water and freezing cycles

Water that has entered cavities, etc. on the surface of structures and has been left there causes special problems. When water freezes, it expands. Salt combined with water and freezing cycles makes the situation even worse (Luodes et al. 2014).

In future weather scenarios, the rain volume will increase in autumns and winters, which means that risks caused by water, detachment caused by melting and freezing cycles will increase risks in the future.

Air pollution and impurities

The deterioration classification has highlighted some damages caused by various air pollutants and other impurities from discoloration to physical damage. From the perspective of stone, the most detrimental impurities include acidic sulphur and nitrogen compounds and salts. Rock types most susceptible to the pollution in urban environments have been found to be carbonate natural stone, limestone and marble.

Air pollution and impurities cause black crust to accumulate on the surface of stones. This is typically uneven and causes mostly diversity in the appearance. (Luodes et al. 2014.)

Structural-physical properties

There is usually no need to take diffusion in account in stone structures. The rock type affects capillarity; for example, granite has no capillarity, whereas marble, sand stone and limestone have much greater capillarity. (Luodes et al. 2014.)

Heat expansion of stone must be taken into account in surface slab solutions (ventilated facades), while heat expansion does not play a part on solid stone structures. (Luodes et al. 2014.)

Salt, chemicals

Climate conditions in the building site, salt contained by the air (for example, at seaside) and pollution, cause many types of damage from detachment to discoloration. Salt used for de-icing damages stones.

Inside buildings, humidity may push through from the concrete structure under the stone slabs on the floor, which can become evident as discoloration. If the floor slabs have been treated, for example, with epoxy or resin coating, the humidity can stay under the coating and break the stone. (Luodes et al. 2014.) Stone slab surfaced concrete sandwich elements present their own problems. In them, salts leaving the structure may cause mainly aesthetic discoloration in the seams of the stone slabs or light runoffs.

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Characteristics of rock types

There are differences in abrasion resistance, porosity, hardness and other properties of various rock types. These physical characteristics are studied in order to get as good a picture of the use characteristics and technical nature of the material with view to designing and implementing the structures as well as possible.

Water absorption capacity

Water absorption capacity (unit: % of the dry weight of the substance) describes how a substance absorbs water. Among other things, this affects the soiling of the stone and changes in colour between dry and wet surfaces. Water absorption capacity also affects the frost resistance. With regard to dense natural stone, water absorption capacity values usually vary between 0.1–0.5 weight-%, while the water absorption capacity value of porous stone can be up as much as 20 weight-%. (Mesimäki 1997, 43.)

Density and porosity

Density of natural stone describes the volumetric weight of stone or the relation between the weight of the stone and volumetric capacity. This allows us to deduce, for example, the composition and density of stone. The higher the porosity of the stone, the lower its density. During the test, an ordinary piece of stone is weighed dry. Natural stone densities vary between 1,800 – 3,100 kg/m^3. (Mesimäki 1997, 43.)

Tensile strength in bending

Tensile strength in bending is considered when dimensioning structural parts subject to bending stress. The value of the measurement is received by bending the test piece until it breaks. With natural stone, these values normally vary between 7 – 20 MPa but individual measurements may vary a great deal The great scattering affects the determination of the factor of safety. (Mesimäki 1997, 43.)

Compressive strength

Compressive strength is used when dimensioning load-bearing structures under compression stress. During the test, the test piece is compressed until it breaks, the compressive strength is calculated with the help of breaking strain and pressure contact area. Compressive strength values of natural stone vary depending on the rock type between 20 – 400 MPa with dense and weather-resistant facade stone compressive strengths varying between 130 – 300 MPa. (Mesimäki 1997, 43.)

Abrasion resistance

Abrasion resistance refers to the durability of the surface in abrasion stress. This is an important perspective when selecting, for example, materials for floorings and other stuctures subject to wear. (Mesimäki 1997, 44.)

The table 1 summarises the results of studies on the physical characteristics of stone performed in conjunction with the natural stone education and research environment development project 2005-2007 (The Geological Survey of Finland (GTK), 2007).

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Class	Granite	Rapakivi	Gneiss	Black	Slate
Water absorption (%)	0,13	0,13	0,08	0,07	0,31
Density (kg/m^3)	2618,95	2658,15	2754,00	2941,11	2715,00
Open porosity (%)	0,40	0,37	0,25	0,21	1,98
Flexural strength (MPa)	16,06	11,11	18,08	20,76	18,60
Flex min exp value	14,00	8,56	13,64	17,91	10,95
Flex after frost (MPa)	15,90	10,51	17,92	21,94	21,15
Flex after frost, min exp value (MPa)	13,52	8,27	13,80	19,26	12,90
Compression (MPa)	192,79	175,08	185,40	198,33	88,00
Compression, min exp value (MPa)	131,95	130,00	127,80	130,33	51,50
Compression after frost (MPa)	193,05	181,68	202,80	209,00	74,50
Capillarity C (g/m^{2}s0,5)	0,35	0,39	0,13	0,07	2,37
Skid dry polished	54,29	51,49	55,10	51,96	
Skid wet polished	10,09	10,33	6,50	10,40	
Skid dry honed	52,52	51,75	56,95	53,04	58,40
Skid wet honed	28,83	33,20	35,20	35,68	53,40
Abrasion test	18,00	17,33		17,17	20,00

Table 1. Properties of natural stone. (The Geological Survey of Finland (GTK), 2007.)

Properties of stone affect their durability from the perspective of the deterioration classification; for example, how the stone absorbs water, or how porous it is, or how hard it is. All these things determine how sensitive to deterioration the rock type is or how durable it is.

All rock types are not suitable for use outside. Rock types best suited for outside use and various granites and soapstone as well as some quartzitic sandstone and broadstone. Soft rock types include sandstone and limestone. (Luodes et al. 2014.)

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Seams and seaming methods


(Paajanen, 2014.)

Sealants have always been used particularly in older stone structures. Currently, stone facades are often thin cladding structures and they are mounted using other methods than sealants. The effect of sealant attaching the stones to each other is important as is evident from the studies discussed below.

The majority of old stone structures in Finland are castles, fortifications and stone churches. These have been expanded, altered and renovated several times during centuries. Different sealant materials and other structural solutions were used at different eras. For example, cement mortar and concrete was used in the renovation of Olavinlinna in the 1950s, while in the 1970s, 1980s, and 1990s Parmu mortar was used (von Kono, 2009, 2).

The first wall renovation was undertaken in Suomenlinna in the 1920s and 1930s. The mortar used at the time had a very high cement content, which meant that the renovated masonry became rock hard. In the 1970s, Parmu mortar was used, which contained cement as bonding agent and had lime putty added to the dry aggregate. Porophore was added to the mortar to make it more porous, but the mortar did not function as a porous mortar and a “weak link” in the middle of the old stone wall, instead the mortar became like artificial stone. In addition, the water that had gotten inside the wall gathered in the original porous and weaker lime mortar and caused damage, especially since the hard renovation mortar prevented it from evaporating. The use of Parmu mortar has since been discontinued. (von Konow 2006, 91 – 92.)

In studies of mortars used in Olavinlinna, it has been found out that there was wet sand instead of hard mortar behind wall seams renovated using Parmu mortar. There were cracks between the restoration mortar and natural stone which created pockets. Wind-driven rain and hard winds may have pushed water inside the wall. (von Konow 2009, 2, 11.)

Parmu mortar, restoration mortar OL-10, is extremely durable cement mortar but according to studies it is questionable that it works well with old lime mortar. Its microstructure is extremely dense and definitely frost-resistant but water possibly entering the wall cannot get out because of the density of the mortar. The cement mortar is clearly denser than the lime mortar, the carbonated lime in the lime mortar is full of hollow micro-spheres and can therefore never be entirely water-resistant. (von Konow 2009, 10 – 11.)

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It has been noted that water trapped in the wall damages and disintegrates mortars weaker than Parmu mortar. According to studies, it is possible that weaker mortar that absorbs water more easily may become saturated with water and consequently become damaged in freezing temperatures. When this happens, the damaged mortar will lose its strength and become more sand-like. (von Konow 2009, 11.)

The climate conditions in Finland require that mortars used have a good frost-resisting capability. Lime mortars resist water if there is no water left in the spheres. Spheres created at the stiffening stage of mortar may receive any water that has been left in the hollows as well as the pressure of water that has frozen there. Studies have shown that some of the already carbonated bonding agent may in some circumstances dissolve and crystallise again incrementally or repeatedly. This phenomenon is known as recrystallization and it increases the density and strength of the mortar, which is believed to be one of the reasons for the strength and durability of old mortars. The climate conditions during brickwork also affect the functionality of the structure. Warm and sunny weather makes mortar dry fast and crack. Too wet and rainy weather causes a film of water in the interface of the mortar and the base, which prevents mortar from sticking. (Holopainen and Helama 2012, 3.)

A study on salt damage mechanisms has been conducted on the Tenaille von Fersen building in Suomenlinna (von Konow et al. 2002). The building in question is part-brick, part-stone built, but many fundamental structural engineering issues, such as dampproofing perspectives, can be applied more extensively as construction guidelines in stone construction.

Problems caused by salt are currently very common in a variety of buildings and structures (von Konow et al. 2002, 15). Salt can enter the structures from groundwater, air (for example, with air pollution or when the construction site is at seashore from sea-air), sealants or other agents used in construction, the use of the building (some special activity in the building) or organic products (human or animal waste (von Konow et al. 2002, 23). The salt study in Suomenlinna has shown that it is important to control humidity and temporal changes of humidity inside the building, for example excess humidity may cause crystallisation of salt (von Konow et al. 2002, 113 - 114).

When the collapsed walls of the land fortress in Loviisa were restored in 2007, particular attention was paid to the choice of mortar to ensure that the structures would function as well as possible. Studies conducted before the restoration found out that the original mortar had been lime mortar and mortar used in earlier repairs had been cement mortar which is not as elastic as hydraulic lime mortar. On the other hand, cement mortar is more water-resistant than lime mortar. Two kinds of mortar were used in the 2007 restoration: Protective mortar made of hydraulic lime and dry aggregate consisting of sand and crushed stone was used in the loopholes and top of the wall. Otherwise, hydraulic lime mortar consisting of two bonding agents, lime putty and hydraulic lime as well as dry aggregate was used. Lime putty is made of air-hardening lime, which is let to soak for one month in water before use. (Metsäranta 2007, 1.)

The significance of selecting the right kind of mortar in restoration and design of stone structures is highlighted by the studies and restoration work conducted at Olavinlinna, land fortress in Loviisa and Suomenlinna. In the worst case, the wrong type of mortar material may cause extensive damages to the stone structure even though the mortar should work as the “weakest link” of the overall structure. Experiences of various mortar materials derived from restoration sites also function as good guidelines for designing new structures. The Suomenlinna study also highlights the significance of the overall humidity control of the building.

Seaming of new ventilated facades is done with elastic sealants. Seaming is done as a separate work using sealants by different manufacturers and seaming work requires drawing up a seaming start document and worksite minutes. Seaming materials used are underfill, sealant and expanding sealing strip and necessary primers.

The weakest link of stone facades are often seaming and the materials used for seaming. Seaming is not strong enough if part of it comes off or is gaping, seaming material ages or causes discoloration of the stone. Seams require controlled property maintenance and regular care. Seaming must be checked with regular service cycles and repeat seaming must be implemented before the structure starts deteriorating. Seaming has been given up entirely in newer facade systems and exposed joints have been taken into use.

Issues affecting the choice of stone

The choice of stone is affected by stone properties related to appearance and technical specifications. As a natural material, stone offers abundant possibilities for solutions of various looks. Treatment of stone increases the available number of appearance-related choices; there are various split, polished, burned and other treatment alternatives available. Abrasion resistance and sensitivity to damage vary according to rock type. The most significant technical properties were discussed above in the section on the properties of rock types.

The intended use often sets demands on the properties of the stone selected. In facades, the stones need to have good weather resistance, in other words, the stone needs to endure the entire planned life cycle of the building without major changes or damages. Bad weather resistance may cause soiling or discoloration of the surface, loss of lustre, disintegration, development of brittleness or deformation of panels.

Things to consider when designing stone structures

Correctly designed and implemented structural details are important in all construction including stone construction. Currently, stone rarely functions as a load-bearing element; stone cladding is typically a structure that protects the wall from the effects of weather.

Renovation and restoration emphasise different issues than new construction. Old stones may be used (at least partly) in renovation and restoration. These projects emphasise the overall functioning of the structure with special emphasis on the selection of correct sealants and control of water movements, in order to ensure that the structure with its old and new parts functions as a whole and the new materials or structural parts do not damage the old structures. At the initial stages of the project, the old structures need to be studied as thoroughly as possible, so that it is known how the structures have been constructed. In new construction, the compatibility of materials and structures and the overall functioning of the

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structures are equally important; in new construction, it should be ensured that the choices made function as planned.

When considering the future changes in circumstances, forecasted changes, such as increase of rain volume especially in winters and autumns have been listed, and many of these will affect the conditions relevant to stones, such as thawing and freezing cycles. Preparing for climate change means for stone structures especially that special attention must be paid to the correctly designed structural details so that water does not the entry into wrong places. Removal of water and preventing water from leaking on the wall must be designed correctly. This applies both to the actual stone structure and structures above it, such as the roof and window and other sheet metal cladding.

Detailing of the facade also greatly affects other appearance-related questions; if the stones get wet unevenly, the facade has a very different look in different weather conditions. In addition to the choice of rock type, it is important to plan how the stone should be treated when designing stone structures. A polished stone floor will be slippery. Rough surface gathers dust and other pollutants on its surface which puts strain on the durability of stone and affects its appearance. The colour of stone also affects how easily dirt is seen, for example, if rough surface treatment is selected for light stone, this will have a great effect on the whole appearance.

The functioning of the overall facade structure is important. Currently, when the stone cladding is supported panel cladding, the ventilation of the facade needs to be well-designed to ensure that humidity does not condensate on the back surface of the stone. In the worst case, humidity can freeze and cause frost strain on the stone.

When too thin stones are selected, the panel may bend.

The choice of brackets affects the durability of stone: wrong type of metal brackets may cause discoloration of the stone surface.

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Future challenges to stone facades

The current trend in structural engineering favours low-density construction engineering. In this context, low-density construction engineering refers to facades with beam, layer or envelope-structured facades with clear ventilation holes or a separate "weather wall". The facade materials are various panels, steel, composites or glass. In low-density construction engineering, the facade material may also be stone, brick or natural stone.

In detached houses the exterior walls often have a frame structure and consequently the facades as a rule ventilated timber facades or brick facades laid in situ. In stone houses, the exterior wall structures may also have full brick, concrete, brick or aerated concrete structures, which means that facades are often of a corresponding material either rendered or lightly coated.

In blocks of flats exterior walls are either concrete sandwich- or curtain-structured element walls on which facade materials are either coated concrete or brick materials. In wooden blocks of flats, the facades are coated timber.

The widest variety of facade materials can be found in public, commercial and office buildings, where facade materials can be freely chosen. The most common facade type used in hall and market construction is steel sandwich panel, which allows the use of either plastic or mineral wool insulation.

Future challenges for the facades will come from, for example, the following factors:

New construction engineering, new materials and structural solutions

The use and utilisation of models at all stages of the project, BIM

New contract and agreement forms, building time and schedules

Changing official practices and control

Energy-technological solutions and environmental classification of buildings, Green Building

Taking into account life cycle costs and new property maintenance

New architectural "national" awakening

Changing environmental and climate conditions in Finland

Consequently, many such properties that are already now self-evident will be demanded from the facades of the future. Economical, energy, environmental and health factors will be emphasised further. Natural stone as material has exactly those qualities that are demanded of next generation facade materials. The most significant weakness of natural stone has been considered its price and the "laboriousness" of stone use both from the perspective of design and worksite engineering. In Finland (2008), only about 0.6% of built facades have stone structure. However, the market share of stone facades is growing. Most stone is used in the facades and foundation walls of public buildings.

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Solid stone structures

In Finland, stone facades of buildings have traditionally been constructed as solid stone structures with natural stone and brick so that an exterior natural stone cladding was attached to directly to load-bearing an insulating massive brick wall with mortar. When needed, this was assisted with forged metal brackets which were protected against corrosion by, for example, tarring them. Tar pitch or creosote could be used between structural layers as insulation for humidity and movement seams. Seaming of the facade was done as jointing with lime-cement mortar. The thickness, lapping and size of facade stones varied according to architectural drawings and dimensioning. There were several choices for outside surface of the stones from polished to rough split.

The weight of a solid stone wall is considerable and the structure requires a good foundation system. The thermal insulation capacity of the structure depends on the thickness of the perforated brick structure and, as a rule, is weak (on a wall 1½ stones approximately 1.0 W/gross floor area). In addition, the structure is sensitive to water damage if humidity for some reason gets inside the structure. Water often enters the structure from the outside as rain or thawing water through badly constructed sheet metal cladding details or as capillary rise from the foundation or the foundation soil. Implemented in this manner, solid stone structure is not “eternal” but requires constant maintenance and regular repairs. Especially in public buildings (schools) and churches solid stone exterior walls have caused problems and required extensive renovation work. Water damage to exterior walls has caused mould damage and interior air problems in buildings. Facade renovation of large-scale stone facades (Tampere Cathedral, Kallio parish church in Helsinki, Helsinki Central Railway Station) have been demanding and challenging renovation projects, where knowledge in stone work has been emphasised. In all these sites, the solid stone walls have had to be disassembles and assembled stone by stone. At the same time, corroded metal brackets of the stones have had to be replaced. The most significant damage has been caused by water and moisture leaks of exterior walls. Another difficulty is these renovations are presented by the replacement of facade stones with replacement stones with similar appearance.

The basic principle of solid stone envelope structure is that the structure is homogenous and of the same or almost same building material throughout. An example of a perfect solid stone exterior wall is a Siporex wall, which is constructed entirely out of aerated concrete. Another good example is the full brick structure, in which the brick is supplemented only with lime- or cement-based substances. In this case the structural-physical behaviour of the structure is fairly straight-forward. The thermal insulation capacity of a structure is based on standing air, dampproofing on controlled saturation and drying (difference in temperature and diffusion) and fire and sound-proofing on the mass (g/m3) of the structure. Solid stone construction is fairly simple, eco-friendly, affordable when considering life cycle costs and has a reasonably low carbon footprint. Therefore, the structure can be considered reasonably ecological as well.

Due to various structural damages and interior air problems in buildings, it might be a good idea to study the future possibilities of using solid stone structures. Low-energy construction and the tightened U value requirements for outer envelope have led to the situation where 300–500 mm. of traditional thermal insulation needs to be used in the exterior walls of buildings. In addition, complete air-tightness is expected

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from envelope structures. It has not been possible to test the joint effect of these in the structural-physical functioning of envelope structures, so the long-term functioning of the structures in their use environments is not known.

Second generation solid stone structures might offer a solution as the "sure-fire" exterior wall structure. In Finland, traditional timber (logs) could be used as a solid structure, while a stone structure and natural stone could be used in more demanding sites. Developing solid stone structures made from natural stone may be challenging or even impossible but for the abovementioned reasons, it should be studied. Considering the thermal properties of natural stone, design of solar-heated or heat-storing facades might be sensible. 'Double-skin facades' combining solid tone structure and separated stone facades and their energy efficiency have not been studied much in Finland with the exception of glass facades.

Ventilated curtain wall structure

In the 1950s–1960s, ventilated cladding solutions started being used in stone facades. 50–75 mm. thick stone slabs were mounted with stainless steel brackets to the load-bearing exterior wall structure. Various mineral wools or foam glass was used as insulation for the exterior wall. Stone panels were seamed after the work with elastic seam putty; exposed joint was also possible albeit rarely used. The size and thickness of the stone panels was decided based on experience and calculations, so that the stone panels did not start bending or the exterior did not become too heavy. The developer could choose the facade stone material with its many surface alternatives.

Later, various structural systems were developed for the market from ventilated stone facades, which used prefabricated steel or aluminium mounting frames, rails, battens or stone brackets. The most popular mounting method is pin or rail mounting. The weight of a facade is approximately xxx kg/m2, which has to be taken into account in structural engineering. The greatest weakness of a curtain stone facade could be considered to be the seams of the wall structure. Seaming should be renewed according to predetermined maintenance cycles. Deformation of stone slabs and frame structure failure also occur. In addition, the facade system is sensitive to mechanical strain, such snow-removal equipment. Separate ventilated curtain stone facade is the most commonly used system in Finland. Current trend favours increasingly light, developed and flexible facade systems.

Ventilated wall panel structure In the 2000s, the stone facades of public buildings in Continental Europe have often been implemented as ventilated curtain stone facades. Most commonly, ventilated facades are built with ceramic panels. However, there has been a significant change in the use of stone materials. In facades, natural stone is often only 10–20 mm. thick outer layer, which means that the structure is approximately 60% lighter than a traditional stone slab facade.

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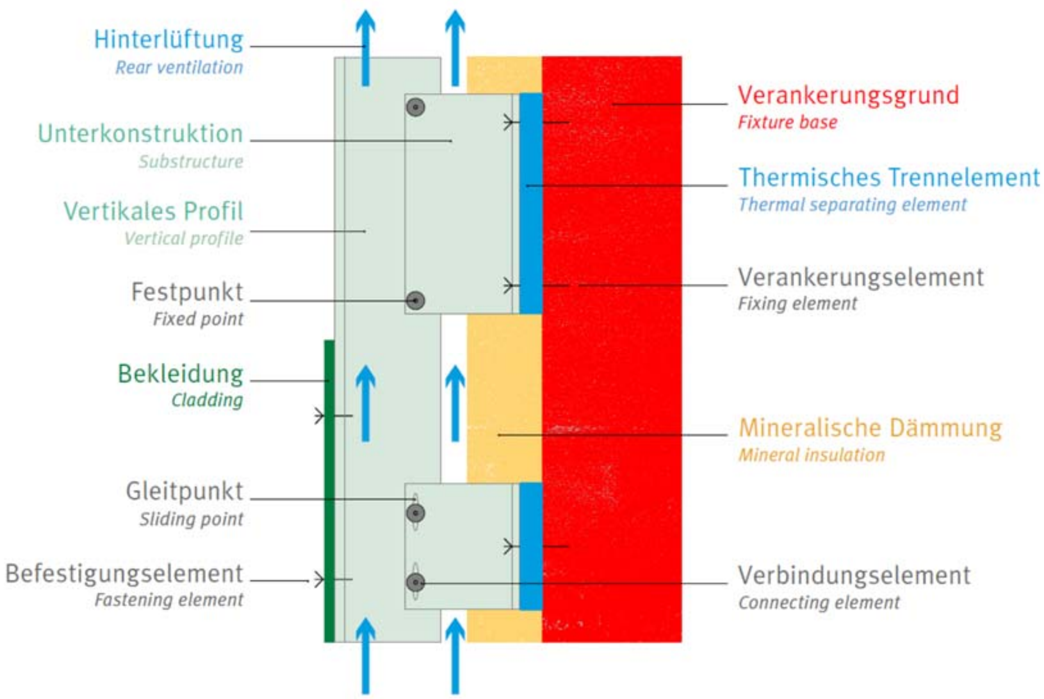
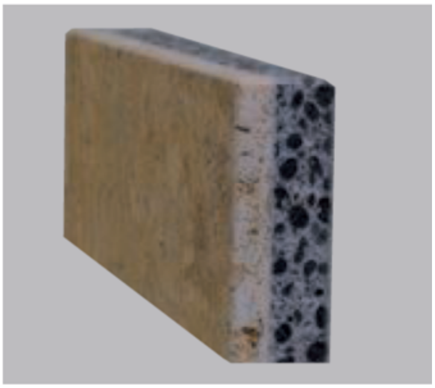
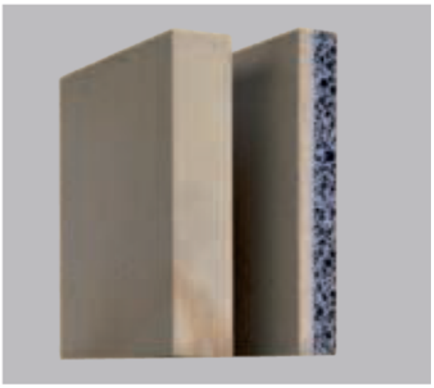


Pictured above the operating principle of a ventilated façade. (Ausgereift bis ins kleinste Detail, 2014.)

Natural stone panels have been bonded to the base panel used as a substructure or to a separate frame and stone panels are left un-seamed. In many systems, the base or frame structure is from aerated or fibre-reinforced concrete. In some systems, the natural stone is bonded to aerated concrete, skeleton or some other substructure. The weight of the facade structure is approximately 30–50 kg/m^2 and the stone facade has exposed joints. The structure allows for various movements and restraint actions caused by the weather and the climate. In some special cases, the structure may also have a tongue-and-groove joint or a weakened-plane joint.





Pictured above the structural details of a natural stone hybrid facade at a refurbishment site. (Lithodecor, 2014.)

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Light and ventilated facade structure with exposed joints is also well-suited for reconstruction. If added exterior installation is used in reconstruction, it is safest to attach it in a traditional manner in the frame structure of the stone facade. Especially in Finland, the exterior surface of the added insulation must be weather-proof and moisture permeable.

Pictured above the structural principle of a ventilated exterior ceramic wall with added insulation used in reconstruction. (ABL, 2014.)

For example, a facade reconstruction system often used in Finland is Stonel lightweight element system. Stonel elements are small steel-framed brick panels but the same principle could possibly be used for constructing a stone panel reconstruction facade system. If the system allowed the use of exposed joints, laborious seaming work could be foregone and the weather-resistance of the system would be good. The small element system should be modular (1M) and allow different stone alternatives. The system should also be suited for repairing foundation walls and plinths.

There are also facade panels using stone on the market, in which the stone panel has been bonded directly with a polyurethane panel operating as a substructure. This gives the facade simultaneous extra insulation.

Just how ecological and applicable to Green Building philosophy stone facades are can be demonstrated with an example. In their studies, DNW (Deutscher Naturwerkstein-Werband) has provided grounds for the use of a stone facade on the Opera Tower office building in Frankfurt-am-Main. The building was designed by architect Christoph Mäckler and it was completed in 2009. The building is a 170-metre high office building with 43 storeys. The choice of facade material saves 23% of energy and 1,800 tonnes of carbon dioxide annually compared to the alternative glass-aluminium facade. The building has 30,000 m^2 of facade and it has reached the gold level in LEED certification. (DNW, 2014.)

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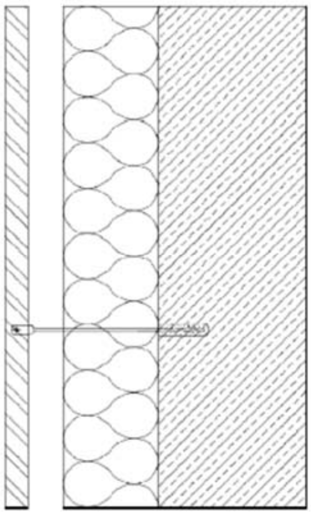
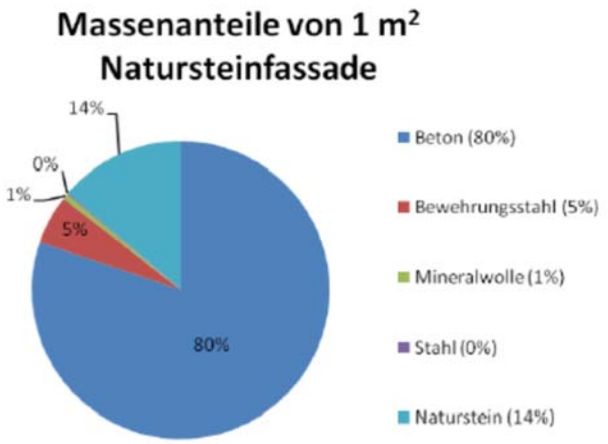
In the site, the energy and life cycle costs of one ventilated stone facade square metre were compared with those of one glass-aluminium facade square metre.

The stone facade structure is traditional ventilated exterior wall structure supported by load-bearing concrete wall, the structure of which is presented below.





(DNW, 2014.)

The glass-aluminium facade is a traditional multiple glass element curtain wall suspended on aluminium profiles with thermal breaks, the structure of which is presented below.

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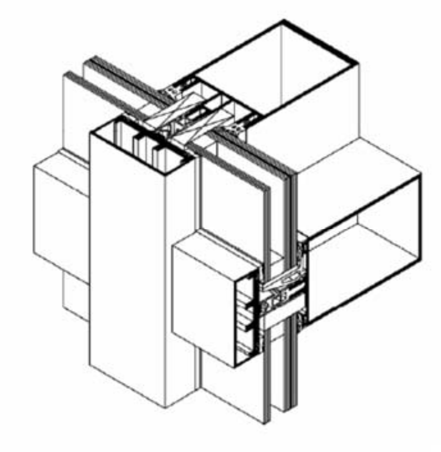
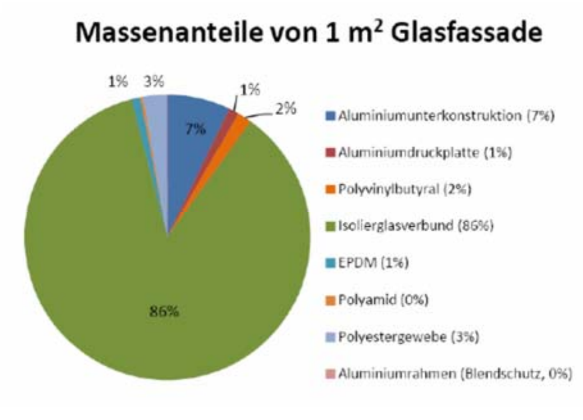
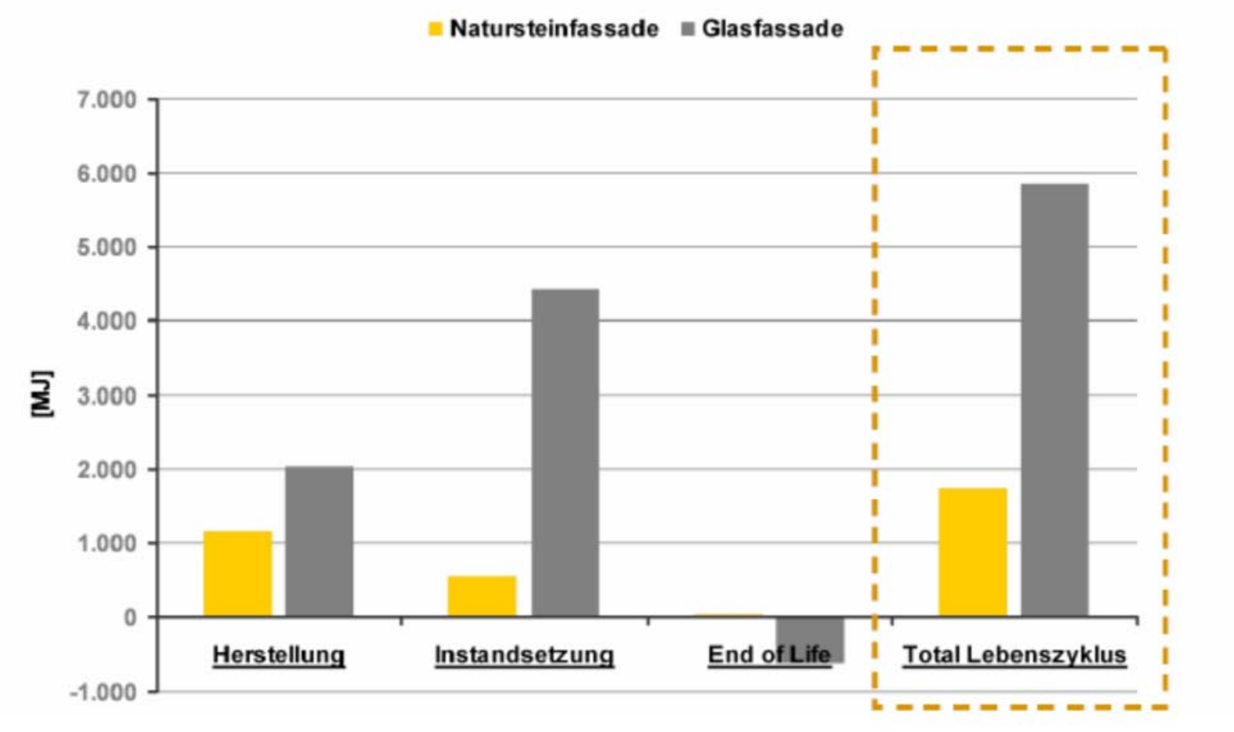




(DNW, 2014.)

With regard to consumption of primary energy, the results showed that the energy costs of the glass-aluminium facade were approximately three times higher than those of the stone facade. The environmental impact of the glass-aluminium facade exceeded those of the stone-concrete facade by approximately 360%. Naturally, the architectural style of the buildings was very different as well.



(DNW, 2014.)

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Therefore, traditional stone facade is an alternative for a traditional lightweight facade, if the energy and life cycle costs of the building are taken into account at the initial design stage. Unfortunately, the choice criterion for facades is often based merely on the developer or the designers preferring or being used to traditional facade materials, or the choice is made purely based on construction costs without any consideration of life cycle costs.

The development and implementation of new facade systems requires product development and official approval at all levels. The designers must have product knowledge, detail-level solutions, libraries and tools suitable for modelling (BIM).

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Summary

Natural stone is an ecological and domestic material, which offers plenty of alternatives for designer, developers and users. The structural-physical properties of natural stone and its behaviour in structures and Finnish conditions in the long run are well-known. Stone structures have long traditions and stone has been considered an almost eternal material, which it almost is when used correctly.

The most difficult technical problems related to the use of stone are related to water and moisture problems, which can be avoided with careful planning and implementation. Changed and changing climate and environmental conditions also increase strain on stone.

Architectonically, stone is a demanding material; it is either loved or hated. Stone is often linked in the mind with public and environmental construction. It is also thought to be valuable and quite expensive, even laborious, construction material, which is why it is seldom used in everyday or housing construction. Concrete has also surpassed traditional stone facades, both the new and reconstruction, and therefore, the development of new flexible and competitive facade systems is topical.

The future stone construction will emphasise the economic, energy, environment and health factors during the entire life cycle of the buildings. We are steered towards this by global increasingly popular environmental classification systems for buildings (Green Building) and quality-awareness of developers and property owners! Consequently, the fact that the building material is produced domestically and locally, in other words its environmental load is reasonably small, becomes increasingly important. This will ensure that Finnish stone will be competitive among other building materials.

Durable, aesthetically pleasing and architectonically high quality surface and facade materials are needed when city centres and built environment are designed. When correctly refined, designed and implemented, natural stone as a facade material has precisely the properties that are expected from next generation stone construction.

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