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REQUIREMENTS FOR REPLACEMENT STONES AT THE COLOGNE CATHEDRAL – A SYSTEMATIC APPROACH TO GENERAL CRITERIA OF COMPATIBILITY

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Abstract

The Cologne cathedral is one of the most outstanding monuments in Northern Europe. Its construction history began in 1248 and the building period lasted for 600 years. The main building material, “Drachenfels trachyte” was extracted from quarries at the nearby “Siebengebirge”. Due to the different construction phases, over 50 different building stone materials were used to build the cathedral.

The cathedral suffers severe stone deterioration, which endangers the structure of the building. Drachenfels trachyte shows pronounced deterioration phenomena such as contour scaling, flaking and structural disintegration to crumbling. Other main building stones, e.g. sandstones, carbonates, and volcanic rocks, show significant degradation as well. For the preservation of the monument it is crucial to find an appropriate replacement material, which is not only suitable for original Drachenfels trachyte but is also compatible with the other rocks.

In the present paper, the mineralogical, petrophysical and moisture properties of the eight main building stones from the Cologne cathedral are determined and discussed in correlation to each other. The strong divergence of the ascertained parameters (i. e mineral composition, porosity, water absorption and saturation, drying characteristics, moisture and thermal dilatation, strength properties, etc.) shows, that the constraints for a replacement material makes it almost impossible to find an ideal stone. The sum of the properties is ranked and their relevance for the specification of replacement criteria is determined in view of the observed deterioration phenomena and processes. This evaluation leads to a systematic approach for the specification of general criteria of compatibility for the selection of replacement materials for historic monuments, which comprise more than one natural building stone material.

Keywords: stone decay, Cologne cathedral, fabric, mineralogy and petrophysical properties, compatibility of building materials, requirements for replacement stones

1. Introduction

The Cologne cathedral has a very long construction history, in which different stone materials were used. Drachenfels trachyte from the quarries of the Siebengebirge is a natural building stone used for construction in Cologne since the Roman period (Wolff

2004). This stone was the construction material for the cathedral during the medieval period. At the beginning of the 16th century the construction was halted and recommenced at the beginning of the 19th century. At that time Drachenfels trachyte was no longer available. Initial renovations were carried out with latite from the “Stenzelberg”, and a few other materials from other quarries of the Siebengebirge. In the middle of the 19th century, the second construction phase used sandstone from “Schlaitdorf”, southern Germany. Later on “Obernkirchen” sandstone from Lower Saxony, and from 1918 until 1940`s “Krensheim Muschelkalk” were implemented. In the 1950’s, the decay resistant basalt lava from “Londorf” was used. The materials presently applied are trachyte from “Montemerlo” (Italy) for the replacement of deteriorated Drachenfels trachyte as well as Czech sandstone from “Bozanov”, which is in use to replace weathered Schlaitdorf sandstone (Scheuren 2004; Schumacher 2004).

2. Decay phenomena

The different building stones of the Cologne cathedral show a large variation of deterioration. The main deterioration phenomena observable in Drachenfels trachyte are erosion and surface recession coexisting with flaking and structural disintegration to crumbling. Back-weathered areas often display stronger further decay in terms of microcracks and crumbling to total fabric collapse. Scaling is observable and very often shows a granular disintegrated zone on the reverse side. Formation of cracks and fissures may also propagate many centimeters in depth into the stone. Drachenfels trachyte is characterized by large phenocrysts of sanidine – up to 7 cm in length. These may cause a different weathering behavior between the matrix and the phenocrysts; e.g. loss of sanidine phenocrysts or loss of matrix. The weathering behavior of the building stones is also controlled by the orientation of the rock fabric. In Drachenfels trachyte the deterioration is more intense when the magmatic foliation, defined by the preferred orientation of sanidine phenocrysts, is parallel to the visible surface of the building stone. A number of breakouts, as a result of the mechanical impact of bombing during WW II, can be observed in Drachenfels trachyte. The flaking can occur in a very pronounced fashion, which eventually leads to structural disintegration and total fabric collapse. There are strong indications that the decay of Drachenfels trachyte is especially critical in the direct neighborhood of carbonate replacement stones (Kraus 1985; von Plehwe-Leisen et al. 2007). In many places the decay starts from the joints, which is indicated by gypsum crusts, flaking and scaling (Graue et al. 2011).

At the Cologne cathedral, very deterioration resistant Obernkirchen sandstone (Grimm 1990) shows the formation of grayish to black crusts as well as the formation of gypsum crusts in sheltered areas. Further severe damage is visible along joints, where the sandstone shows breakouts due to spalling, especially on the decorative parts, e.g. pilaster strips.

Already Kraus (1985) and Grimm (1990) mentioned the characteristic degradation of Schlaitdorf sandstone at the Cologne cathedral. Due to the carbonate binder (app. 14%) gypsum formation is observed leading to massive scaling and flaking as well as granular disintegration. Deterioration in form of rounding and notching is also typical for Schlaitdorf sandstone.

At present little is known about the deterioration behavior of Montemerlo trachyte at the Cologne cathedral, since this stone has only been implemented in recent years.

However, Lazzarini et al. (2008) report of exfoliation and flaking, powdering and alveolic weathering for Montemerlo trachyte in Venice, Italy.

Stenzelberg latite and Londorf basalt lava have high weather resistivity. Due to its high porosity, Londorf basalt lava is susceptible to microbiological action. Stenzelberg latite shows typical formation of scales with a thickness of 2–3 mm.

Bozanov sandstone shows spalling along edges when mounted, which is problematic for masonry works. Přikryl et al. (2010) report on granular disintegration, scaling, flaking, crust formation as well as blistering, fracturing, salt efflorescences and alveoli formation for medium grained Bozanov sandstone.

Krensheim Muschelkalk is a deterioration resistant rock. This carbonate building stone shows massive gypsum crust formation in rain protected areas. On surfaces exposed to rain, solution phenomena (e.g. microkarst) can be observed leading to surface roughness and loss of shape of figural parts.

3. Building stones of the Cologne cathedral

3.1 Petrography

Drachenfels trachyte is a light gray, partially yellowish porphyritic trachyte with phenocrysts of sanidine up to 7 cm in size enclosed in a fine grained matrix composed mainly of feldspar and quartz. The phenocrysts can show a preferred orientation in the matrix tracing the magmatic foliation. The rock comprises sanidine (50%), plagioclase (24%), quartz (13%), augite (5%), biotite (5%), ore (2%) and apatite, zircon and sphene (1%). In places calcite occurs accompanied by iron oxides, indicating the influence of hydrothermal fluids. Interstitial volcanic glass, partially recrystallised and altered to montmorillonite is observed between the feldspar laths of the matrix. Pyrite and aggregates of pyrite (partly altered to hematite and limonite?) are found in cavities (Grimm 1990).

Trachyte of Montemerlo shows a quasi-isotropic and homogenous fabric. Feldspar crystals (0.5–10 mm), biotite (< 2mm) and amphibole float in a gray to yellowish microcrystalline matrix composed of anorthoclase, sanidine, plagioclase and seldom quartz. The rock’s composition shows K-feldspar (53%), plagioclase (15%), quartz (8%), amphibole (8%), biotite (5%), pyrite (7%) and calcite (4%) (Koch 2006).

Stenzelberg latite is a medium gray, porphyritic, and in part porous latite. The micro to cryptocrystalline matrix (77%) is mainly composed of plagioclase and sanidine. Plagioclase (14%), hornblende with individual grain sizes up to 10 cm (5%), augite (1%), and biotite (1%) occur as phenocrysts. Accessory minerals are apatite, sphene, zircon and ore minerals (Grimm 1990).

Obernkirchen sandstone is a medium grained, moderately to well-sorted quartz arenite of white to orange color with maximum grain size of 300 microns. The rock is composed of monocrystalline quartz (98 %), muscovite, zircon, tourmaline, rutile and opaque minerals. The fabric is grain-supported with sutured grain contacts. The matrix (ca. 5%) consists of authigenic kaolinite, rare silica and iron oxide patches (Dienemann and Burre 1929; Grimm 1990; Morales et al. 2007).

Schlaitdorf sandstone is a coarse grained and well-sorted arenite, whitish to yellowish with often parallel, angular and cross bedding. The detrital fraction (65%) is represented by quartz (72%), rock fragments (12%), feldspar (2%) and cement (14%). The cement consists of coarse grained dolomite, in parts silica and rarely illite and kaolinite. The main accessories (< 1%) are apatite, zircon, tourmaline and opaque minerals (Grimm1990).

Weakly cemented Bozanov sandstone is a coarse to medium grained arkosic arenite of light gray to yellow color. The mineralogical composition is given by quartz (79%), rock fragments (10%), feldspar (5%), clay minerals (smectite and kaolinite, around 5%) and accessories like biotite, zircon and opaque minerals (Koch 2001; Přikryl et al. 2010).

Krensheim Muschelkalk is a light-colored, brown-grayish, fine and porous limestone very rich in shell fragments. It is classified as a densely packed bio(micro)sparite after Folk (1962). Mussel and brachiopod shells of 5–7 mm sized are densely packed in a fine calcite matrix. The components are oriented parallel to the bedding, showing a moderate sorting. The composition consists of 75% biogenic components mainly with micritic rendering, 5% cement and 20% pores (Grimm 1990; Siegesmund et al. 2010).

Londorf basalt lava is a brownish to bluish gray basalt. The fabric is fine to medium grained with hyaloophitic fractions. The rock is composed of plagioclase (50%), clinopyroxene (25%), olivine (15%) and ore minerals (ilmenite and magnetite around 10%). Cryptocrystalline accessories (< 1%) and glass (up to 50%) also occur. The rock is highly porous and the pores are often coated by light-gray bluish secondary zeolites (Grimm 1990; Steindlberger 2003).

3.2 Petrophysical properties

The investigated stones show medium porosities from 11.8% (Montemerlo trachyte) to 19.9% (Schlaitdorf sandstone), except Stenzelberg latite, which belongs to low porosity stones with a porosity of 8.5% (Tab. 1). Drachenfels trachyte has a porosity of 11.9%. Densities range from 2.10 g/cm^3 to 2.52 g/cm^3 (Tab. 1).

Table 1. Bulk and matrix density, porosity, mean and mode pore radius, capillary water uptake, saturation coefficient, water vapor diffusion resistance and water vapor adsorption (Graue et al. 2011).

Rock type	Bulk density (g cm^{-3})	Matrix density (g cm^{-3})	Effective porosity (vol. %)	Mean pore radius (µm)	Mode pore radius (µm)	Capillary water uptake (w-value) (kg/m$^2\sqrt{}$h	Saturation degree (S-value)	Water vapor diffusion resistance factor (µ)		Water vapor adsorption (wt. %)
								Z	X	
Drachenfels trachyte	2.33	2.64	11.9	0.414	1.334	0.55	0.74	37.38	17.91	1.88
Stenzelberg latite	2.46	2.69	8.5	0.017	0.013	0.3	0.76	56.39	50.2	2.78
Schlaitdorf sandstone	2.1	2.63	19.9	2.891	33.497	6.68	0.64	20.56	16.93	0.38
Obernkirchen sandstone	2.16	2.65	18.6	0.821	3.35	1.26	0.64	15.89	14.95	0.72
Krensheim Muschelkalk	2.25	2.68	16.0	1.501	8.414	1.3	0.59	69.45	51.25	0.29
Londorf basalt lava	2.52	2.92	13.1	0.621	21.135	0.39	0.59	37.78	38.6	1.62
Bozanov sandstone	2.17	2.63	17.8	5.953	21.135	6.9	0.65	16.51	19.69	0.75
Montemerlo trachyte	2.35	2.66	11.8	0.108	0.211	0.99	0.71	40.49	31.82	1.11

The pore size distributions (PSD) of the investigated stones are unimodal – except of Krensheim Muschelkalk and Londorf basalt lava (Rüdrich and Siegesmund 2007). Schlaitdorf and Bozanov sandstone have a broader distribution of pores ranging from 0.0064–82 µm with a clear peak of pores at > 10 µm. Obernkirchen sandstone has a narrower distribution in the range of 0.0064–6.4 µm and Drachenfels trachyte in the range of 0.0082–2.8 µm. The PSD of Montemerlo trachyte is limited from 0.0064–1 µm and that of Stenzelberg latite from 0.0064–0.28 µm with a relatively narrowed pore radii maximum. Krensheim Muschelkalk and Londorf basalt lava show bimodal PSD (Graue et al. 2011).

3.3 Moisture properties

Analogous to Snethlage 2005 and Siegesmund and Dürrast 2011, Drachenfels trachyte, Stenzelberg latite and Londorf basalt lava show low capillary water absorption (w < 0.5 $kg/m^2\sqrt{h}$). Montemerlo trachyte, Obernkirchen sandstone and Krensheim Muschelkalk have a medium value (1–1.5 $kg/m^2\sqrt{h}$); Schlaitdorf and Bozanov sandstone show high capillary water absorption (6.5–7 $kg/m^2\sqrt{h}$) (Graue et al. 2011). The values are listed in Table 1.

Based on the measured data of pore radii and capillary water absorption, the stones can be divided into three groups (after Snethlage 2005): 1) Stenzelberg latite, Londorf basalt lava and Drachenfels trachyte have small mean pore radii and low capillary water absorption (w-value); 2) Montemerlo trachyte, Krensheim Muschelkalk and Obernkirchen sandstone have medium pore radii in the lower to medium range of capillary active pore sizes and medium capillary water absorption; 3) Schlaitdorf and Bozanov sandstone with large mean pore radii have high water absorbing coefficients.

The values for the water saturation (s-value) of the investigated stones range from 0.59–0.76 (Tab. 1). Krensheim Muschelkalk and Londorf basalt lava show the lowest s-values. Schlaitdorf, Obernkirchen and Bozanov sandstone are in a medium range. Drachenfels and Montemerlo trachyte as well as Stenzelberg latite are stones with higher s-values.

In terms of water vapor adsorption Stenzelberg latite shows the highest mass increase of 2.78 wt. % at 95% RH and Krensheim Muschelkalk the lowest value (0.29 wt. %) (Tab. 1). Drachenfels trachyte and Londorf basalt lava also show a relatively high water vapor adsorption, whereas Montemerlo trachyte, Obernkirchen and Bozanov sandstone have medium water vapor adsorption. Schlaitdorf sandstone only shows a small mass increase (Tab. 1). Stenzelberg latite, Londorf basalt lava and Drachenfels trachyte show a hysteresis in their sorption-desorption-behavior, indicating that the stone material dries slower with descending relative humidity and still contains a residue of moisture as a possible indication of capillary condensation.

In respect to the water vapor diffusion resistance Krensheim Muschelkalk and Stenzelberg latite have a high resistance. Drachenfels and Montemerlo trachyte as well as Londorf basalt lava show medium resistance. The several sandstones have the highest permeability of the investigated stones (Tab. 1). Drachenfels trachyte shows a remarkable directional dependency of water vapor diffusion resistance (Tab. 1). A higher resistance correlates with a higher amount of micropores: capillary condensation takes place in micropores, which holds back water due to solvent water diffusion. This leads to capillary suction (retention), which is much slower than water vapor diffusion (Snethlage 1984). Only Krensheim Muschelkalk does not fit this correlation.

Hygric dilatation (in the range between 0% and 95% RH) and hydric dilatation (water saturated) were measured. In general, moisture dilatation is low. Montemerlo trachyte has the highest hydric dilatation (0.316 mm/m). The values for the hygric dilatation of Montemerlo trachyte are somewhat higher than that of Drachenfels trachyte.

High moisture swelling was measured as well in Drachenfels trachyte, Londorf basalt lava and Stenzelberg latite. The latter shows a significant hygric dilatation (0.231 mm/m) due to its high content of micropores (Rüdrich et al. 2011). Obernkirchen sandstone has medium moisture related swelling. Schlaitdorf and Bozanov sandstone have low moisture dilatation. The length change of the moisture expansion in Krensheim Muschelkalk is negligible (Tab. 2). With increasing relative humidity a sharper increase of hygric expansion can be observed at around 80–85% relative humidity (Graue et al. 2011).

Table 2. Thermal expansion coefficient and hygric dilatation (Graue et al. 2011).

Rock type	**Thermal dilatation coefficient**			**Hydric dilatation**	
	x ($10^{-6}K^{-1}$)	**z** ($10^{-6}K^{-1}$)	**anisotropy** (%)	**x** (mm/m)	**z** (mm/m)
Drachenfels trachyte	5.32	6.05	12	0.253	0.236
Stenzelberg latite	9.41	7.36	21.7	0.196	0.23
Schlaitdorf sandstone	9.65	11.96	19.3	0.025	0.025
Obernkirchen sandstone	11.6	12.17	4.6	0.089	0.06
Krensheim Muschelkalk	4.75	6.82	30.3	0	0.005
Londorf basalt lava	5.32	5.78	8	0.226	0.186
Bozanov sandstone	8.78	8.65	1.5	0.027	0.013
Montemerlo trachyte	6.25	4.65	25.5	0.291	0.316

3.4 Thermal dilatation

In terms of thermal dilatation only for Obernkirchen and Schlaitdorf sandstone higher thermal expansion coefficients are detected. The other stones show low to medium thermal expansion and no residual strain (Tab. 2).

3.5 Strength properties

The compressive strength varies between 45.1 N/mm^2 and 126.4 N/mm^2 (Tab. 3). Stenzelberg latite has the highest compressive strength (126.4 N/mm^2), while the average strength values for Krensheim Muschelkalk as well as Schlaitdorf and Bozanov sandstone are less than 50 N/mm^2. Only Stenzelberg latite belongs to the high strength rocks, while rocks with compressive strength values between 55 N/mm^2 and 70 N/mm^2 belong to the low strength rocks (Mosch 2008), as there are Drachenfels trachyte and Londorf basalt lava. Obernkirchen sandstone and Montemerlo trachyte display higher uniaxial compressive strength values. A directional dependency is detected for Obernkirchen sandstone and Montemerlo trachyte (Tab. 3).

The flexural strength values of the investigated rocks cover the range between 4.0 N/mm^2 (Bozanov sandstone) and 15.7 N/mm^2 (Stenzelberg latite) (Tab. 3). Londorf basalt lava has a high flexural strength, whereas Schlaitdorf sandstone, Drachenfels and Montemerlo trachyte show medium flexural strength values. Obernkirchen sandstone and Krensheim Muschelkalk display somewhat higher flexural strength values (Tab. 3).

The tensile strength measured using the Brazilian Test varies between 3.1 N/mm^2 (Drachenfels trachyte) and 9.7 N/mm^2 (Stenzelberg latite), depending on the sample and direction of load with respect to the rock fabric. Londorf basalt lava shows a medium tensile strength. Obernkirchen, Schlaitdorf and Bozanov sandstone, Krensheim Muschelkalk and Montemerlo trachyte have a lower tensile strength (Tab. 3) (Graue et al. 2011).

Table 3. Uniaxial compressive strength, tensile strength and flexural strength of the investigated rocks in non-weathered condition (Graue et al. 2011).

Rock type	**Compr.strength (N/mm^2)**		**Tensile strength (N/mm^2)**		**Flexural strength (N/mm^2)**	
	Z	*X*	*Z*	*X*	*Z*	*X*
Drachenfels trachyte	65.54	66.59	3.087	3.674	5.999	6.1
Stenzelberg latite	126.41	120.02	9.735	8.621	15.707	9.881
Schlaitdorf sandstone	47.59	51.44	3.256	3.343	6.492	5.733
Obernkirchen sandstone	86.72	76.29	4.594	4.669	7.992	6.825
Krensheim Muschelkalk	48.35	52.74	4.498	4.544	8.467	6.763
Londorf basalt lava	63.1	72.18	5.099	5.921	12.567	12.749
Bozanov sandstone	45.1	52.08	3.462	3.343	3.975	4.41
Montemerlo trachyte	75.53	84.75	3.439	3.68	6.725	8.195

4. Correlation of fabric, mineralogical, petrophysical properties, and decay processes

Drachenfels trachyte has a porphyritic fabric with strong magmatic foliation. Large phenocrysts of sanidine are embedded with preferred orientation in a matrix with strongly aligned microcrystalline feldspar laths. The fabric can be divided in three structural components: the large phenocrysts, secondly the microcrystalline matrix, composed mainly of feldspar, and third a mesostasis consisting mainly of recrystallized interstitial volcanic glass. As mentioned by Grimm 1990 this is partially altered to montmorillonite.

In contrast to the relatively high porosity of 12% and the high ratio of capillary active pores (84%), the stone shows a low capillary water uptake (0.55 $kg/m^2\sqrt{h}$). This may indicate a lack of connectivity of the pore space. The water vapor adsorption and the saturation degree measured were high, analogous to the guidelines of Snethlage 2005. Larger mineral grains show a lot of cracks and breakages, which are to be considered as part of the pore space. Drachenfels trachyte shows medium water vapor diffusion resistance and drying is retarded. Kraus 1985 reports that within 15 days the tested stone samples still contain rest moisture. This water has to be released via water vapor diffusion. The strength properties of the stone are medium to low: low compressive strength, medium flexural strength, very low tensile strength. Moisture dilatation is raised compared to the other eight investigated stones, thermal dilatation is little.

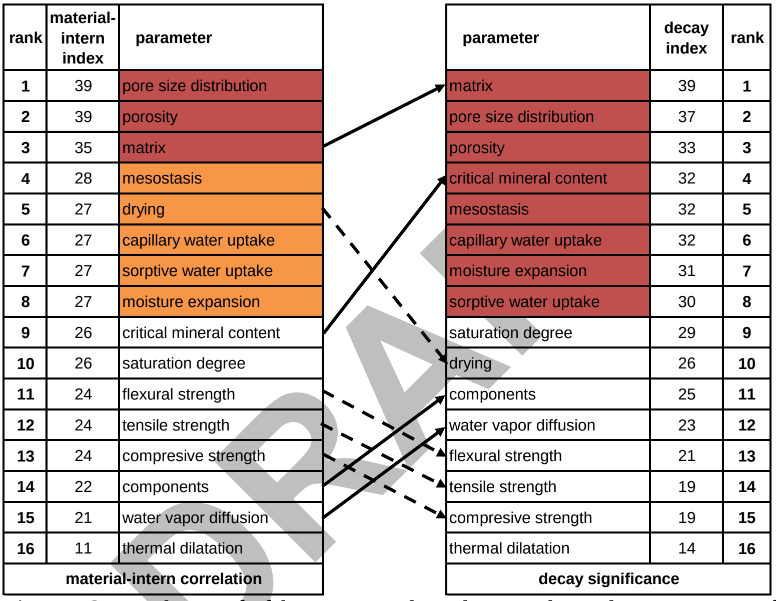
Drachenfels trachyte is very inhomogeneous not only in respect of grain sizes but also in terms of the mineralogical composition of the structural components (phenocrysts, matrix and mesostasis) and their specific properties. Phenocrysts and matrix consist of chemically fairly stable components in comparison to the mesostasis. The recrystallized glass in the mesostasis is liable to chemical decay impact, and the fractions already altered to montmorillonite enhance deterioration processes due to the swelling properties of these clay minerals. Even though capillary water uptake is low, the high porosity, saturation degree and water vapor adsorption as well as the retarded drying suggest a susceptibility to moisture related deterioration processes. These parameters, which are significant for Drachenfels trachyte, indicate that wetting-drying cycles are not very pronounced, but the stone stays humid over long periods of time. This involves a significant capacity for the adsorption and the transportation of pollutants and guarantees sufficient water supply for the degradation processes. In these terms, direct mechanical material reaction, e.g. moisture dilatation, can be considered minor, but pollution impact and salt weathering become more important.

Drachenfels trachyte		fabric			cmc	pore space properties		moisture properties						therm. dil.	strength properties				
		A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	extrinsic impact correlation of the parameters (decay index)	
A	components		3	2	2	1	1	1	1	1	1	2	1	2	2	3	2	**25**	A
B	matrix	0		3	2	3	3	3	3	3	3	3	2	2	2	2	2	**39**	B
C	mesostasis	0	0		3	3	3	2	3	2	2	3	1	2	1	1	1	**32**	C
D	critical mineral content (cmc) (e.g. calcite, clay minerals)	2	2	3		3	2	3	3	2	2	3	2	2	1	1	1	**32**	D
E	porosity	1	3	3	2		3	3	2	2	2	2	2	1	2	2	2	**33**	E
F	pore size distribution	1	3	2	2	3		3	3	2	3	3	3	2	2	2	2	**37**	F
G	capillary water uptake	1	3	2	1	3	3		1	3	1	3	3	0	2	2	2	**32**	G
H	sorptive water uptake	1	3	2	2	3	3	1		3	2	3	3	0	1	1	1	**30**	H
I	saturation degree	1	3	2	1	3	2	3	3		0	3	2	0	2	2	2	**29**	I
J	water vapor diffusion	2	3	2	2	3	3	1	2	0		1	3	0	1	1	1	**23**	J
K	moisture expansion	1	2	3	3	2	3	3	3	2	0		1	0	1	2	1	**31**	K
L	drying	1	2	1	2	2	3	3	3	3	3	2		0	1	1	1	**26**	L
M	thermal dilatation	2	2	2	1	2	2	0	0	0	0	0	0		1	1	1	**14**	M
N	compresive strength	3	3	2	1	3	3	1	1	1	0	1	1	0		0	0	**19**	N
O	flexural strength	3	3	2	1	3	3	1	1	1	0	1	1	0	2		0	**21**	O
P	tensile strength	3	3	2	1	3	3	1	1	1	0	1	1	0	2	2		**19**	P
		material intern correlation of the parameters																	
		22	**35**	**28**	**26**	**39**	**39**	**27**	**27**	**26**	**21**	**27**	**28**	**11**	**24**	**24**	**24**		
		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P		

Figure 1. Correlation of fabric, mineral and petrophysical parameters of Drachenfels trachyte in terms of their significance for the material behavior (lower left triangle) and the decay characteristics (upper right triangle)

In a matrix analogous to Visser and Mirwald 1998, the afore described fabric and pore space parameters as well as the petrophysical properties of Drachenfels trachyte are evaluated from 0 to 3 (rating numbers) in terms of their significance to each other for the material behavior (Fig. 1). This material-intern correlation points out the significance of distinct parameters in respect to the characteristic properties of this stone, e.g. water up take strongly correlates with porosity and PSD (rating number 3), whereas thermal dilatation is not interrelated to moisture properties (rating number 0). The sum of these rating numbers of one parameter is the degree of the material-intern correlation of the parameters, the “material index” of each parameter. This is shown by the lower left side of the matrix (Fig 1). In the upper right part of the matrix the parameters are correlated to each other in terms of their significance for the deterioration processes, again from 0 to 3, giving the "decay index" for each parameter.

The correlation of the material parameters shows, that in the case of Drachenfels trachyte mainly pore space properties such as PSD and porosity, and fabric parameters, characterized by the specific features of the matrix and mesostasis, as well as moisture properties, e.g. drying and capillary water uptake, determine the behavior of the stone (Fig 2). In respect to the decay of the stone mainly fabric and pore space parameters as well as moisture properties control the deterioration processes. Strength and thermal properties are of minor impact (Fig 2).



rank	material-intern index	parameter
1	39	pore size distribution
2	39	porosity
3	35	matrix
4	28	mesostasis
5	27	drying
6	27	capillary water uptake
7	27	sorptive water uptake
8	27	moisture expansion
9	26	critical mineral content
10	26	saturation degree
11	24	flexural strength
12	24	tensile strength
13	24	compresive strength
14	22	components
15	21	water vapor diffusion
16	11	thermal dilatation
	material-intern correlation	

parameter	decay index	rank
matrix	39	1
pore size distribution	37	2
porosity	33	3
critical mineral content	32	4
mesostasis	32	5
capillary water uptake	32	6
moisture expansion	31	7
sorptive water uptake	30	8
saturation degree	29	9
drying	26	10
components	25	11
water vapor diffusion	23	12
flexural strength	21	13
tensile strength	19	14
compresive strength	19	15
thermal dilatation	14	16
decay significance		

Figure 2. Ranking of fabric, mineral and petrophysical parameters of Drachenfels trachyte in terms of their significance for the material behavior and the deterioration, indicating eight "key parameters" for the specification of replacement criteria.

5. Relevance for replacement criteria of potential building stones

The correlation of the parameters and their ranking in terms of the material behavior and the deterioration impact (Fig. 2), indicate the relevance for the specification of replacement criteria. The material behavior of Drachenfels trachyte is determined by pore space parameters and fabric as well as moisture properties; especially PSD, porosity, capillary water uptake and water vapor adsorption. In terms of deterioration besides the mentioned parameters also matrix, mesostasis and moisture dilatation become more pronounced. The eight parameters characterize Drachenfels trachyte as building stone and are significant for the behavior of the stone in terms of extrinsic impact and decay. These are the "key parameters" a replacement stone for Drachenfels trachyte should be compatible with.

In general, restoration and conservation measures have to avoid any import of potential harmful substances by new materials, e.g. critical mineral components in a replacement stone. Further, the optical properties of the replacement stone should be similar to the original material considering aging and patination. In respect to petrophysical criteria, a replacement stone for Drachenfels trachyte should have a comparable PSD and porosity as well. Moisture dilatation should not be pronounced and capillary water uptake as well as water vapor adsorption should be low. Generally the s-value should be less than 0.75. Although strength and thermal properties play a minor role in deterioration processes in Drachenfels trachyte, a replacement stone should be in a range of 80-120% of the strength values (Snethlage 2005) and thermal dilatation should be less than the original stone.

The actual replacement stone for Drachenfels trachyte at the Cologne cathedral is Montemerlo trachyte from Italy. If the two stones are compared in respect to the mentioned constraints, it is to ascertain that the mineralogical composition and optical properties match perfectly. Porosity is similar; in comparison to Drachenfels trachyte, the PSD in Montemerlo trachyte shows higher ratio of micropores (37:63), in Drachenfels trachyte the ratio of micro to capillary pores is 16:84 (Graue et al. 2011). Moisture dilatation is slightly pronounced in Montemerlo trachyte (Tab. 2) and capillary water uptake is higher, but water vapor absorption and s-value are lower than in Drachenfels trachyte (Tab. 1). In terms of strength properties Montemerlo trachyte is a slightly stronger stone, averagely 112%, which is in the range of constraints. Thermal dilatation of Montemerlo trachyte is comparable to the Drachenfels stone, as well is drying.

In general, the parameters of Drachenfels and Montemerlo trachyte are in a close comparability. The higher ratio of micropores, the higher capillary water uptake and the slightly pronounced moisture dilatation of Montemerlo trachyte can be critical. In resemblance to the observation by Lazzarini et al. (2008), Montemerlo trachyte shows little resistance to salt deterioration experiments. It was the first of eight investigated stones from the Cologne cathedral losing 50% of its weight after 19 cycles; Drachenfels trachyte is second after 30 cycles.

6. Conclusions

The different building stones employed at the Cologne cathedral show a diverse petrography and mineralogical composition as well as a broad variety of petrophysical properties. To understand possible interactive deterioration processes it is important to determine the basic petrophysical data. For Drachenfels trachyte the parameters are correlated to each other in terms of their significance for the characterization of the stone as well as their relevance in respect to deterioration processes. The determined “key parameters” mark the critical factors. A replacement stones has to meet these key factors within a certain range. This evaluation leads to a systematic approach for the specification of general criteria of compatibility for the selection of replacement materials for historic monuments, which comprise more than one natural building stone material.

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References

Dienemann W, Burre O 1929. *Die nutzbaren Gesteine Deutschlands und ihre Lagerstätten mit Ausnahme der Kohlen, Erze und Salze*. Stuttgart: Enke.

Folk RL 1962. ‘Spectral subdivision of limestone types’. In *Classification of carbonate rocks,* Ham WE (ed.) 62–84. Tulsa: AAPG.

Graue B, Siegesmund S, Middendorf B 2011. ‘Quality assessment of replacement stones for the Cologne Cathedral: mineralogical and petrophysical requirements’. *Environ Earth Sci* **63**:1799–1822.

Grimm WD 1990. *Bildatlas wichtiger Denkmalgesteine der Bundesrepublik Deutschland.* München: *Arbeitsheft Bayer. Landesamt für Denkmalpflege* **50**.

Koch R 2001. ‘Zur Geologie und Fazies eines Sandsteins aus Nordost-Tschechien’. Unpubl. report. University of Erlangen.

Koch R 2006. ‘Trachyte aus dem Colli Euganei, Norditalien’. In *Modellhafte Entwicklung von Konservierungskonzepten für den stark umweltgeschädigten Trachyt an den Domen zu Köln und Xanten*, Schock-Werner B (ed.) 9–42. Köln: Selbstverlag.

Kraus K 1985. ‘Experimente zur immissionsbedingten Verwitterung der Naturbausteine des Kölner Doms ’. Ph.D. dissertation. University of Cologne.

Lazzarini L, Antonelli F, Cancelliere S, Conventi A 2008. ‘The deterioration of Euganean trachyte in Venice’. In *Proc. 11th Int. Congr. Deterioration and Conservation of Stone*, Lukaszewicz J, Niemcewicz P (eds.) 153–162. Torun: Copernicus Univ. Press.

Mosch S 2008. ‘Optimierung der Exploration, Gewinnung und Materialcharakterisierung von Naturwerksteinen’. Ph.D. dissertation. University of Göttingen.

Morales Demarco M, Jahns E, Rüdrich J, Oyhantcabal P, Siegesmund S 2007. ‘The impact of partial water saturation in rock strength: an experimental study on sandstone’. *ZDGG* **158(4):**869–882.

Přikryl R, Weishauptová Z, Novotná M, Přikrylová J, Šťastná A 2010. ‘Physical and mechanical properties of the repaired sandstone ashlars in the facing masonry of the Charles Bridge in Prague’. *Environ Earth Sci.* **63**:1623–1639.

Rüdrich J, Siegesmund S 2007. ‘Salt and ice crystallisation in porous sandstones’. *Environ Geol.* **52**:225–249.

Rüdrich J, Kirchner D, Seidel M, Siegesmund S 2005. ‘Beanspruchungen von Naturwerksteinen durch Salz- und Eiskristallisation im Porenraum sowie hygrische Dehnungsvorgänge’. *ZDGG* **156(1)**:59–73.

Scheuren E 2004. ‘Kölner Dom und Drachenfels’. In *Steine für den Kölner Dom,* Schock-Werner B, Lauer S (eds.) 22–45. Köln: DomVerlag.

Schumacher T 2004. ‘Steine für den Dom’. In *Steine für den Kölner Dom,* Schock-Werner B, Lauer S (eds.) 46–77. Köln: DomVerlag.

Siegesmund S, Grimm WD, Dürrast H, Rüdrich J 2010. ‘Limestones in architecture’. In *Limestone in the built environment: present day challenges to preserve the past,* Smith B, Gomez-Heras M, Viles H, Cassar J (eds.) 37–59. vol 331. London: Geol. Society.

Siegesmund S, Dürrast H 2011. ‘Physical and mechanical properties of rocks’. In *Stone in architecture,* Siegesmund S, Snethlage R (eds.) 97–225. Berlin: Springer.

Snethlage R 1984. *Steinkonservierung 1979–1983*. München: *Bayer. Landesamt für Denkmalpflege*.Snethlage R 2005. *Leitfaden Steinkonservierung*. Stuttgart: Fraunhofer IRB.

Steindlberger E 2003. *Vulkanische Gesteine aus Hessen und ihre Eigenschaften als Naturwerksteine*. Wiesbaden: *Geol Abhdl. Hessen* **110**.

Visser H, Mirwald P 1998. ‘Baumberger Kalksandstein – Materialeigenschaften und Schadenspotential’. In *Die Steinskulpturen am Zentralbau des Jagdschlosses Clemenswerth/Emsland,* LAD Nieders. 26–45. Hannover: Selbstverlag **15**.

von Plehwe-Leisen E, Leisen H, Wendler E 2007. ‘Der Drachenfels-Trachyt – ein wichtiges Denkmalgestein des Mittelalters’. *ZDGG* **158(3)**: 985–998.

Wolff A 2004. ‘Steine für den Dom’. In *Steine für den Kölner Dom,* Schock-Werner B, Lauer S (eds.) 8–21. Köln: DomVerlag.