PROPERTIES OF ROCKS IN CIVIL AND RURAL ENGINEERING

by

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INTRODUCTION

Civil and rural engineers exploring in foreign countries often have to know in a short time the quality and durability of rocks and gravels with which they are not familiar as regards their suitability for certain purposes. Moreover, the choice of the material to be used is mostly large when the object is the construction of railway embankments or dams in countries where various geological formations occur. By mechanical testing the quality of a rock in wet or dry condition against mechanical forces perpendicular or parallel to the bedding plane, can be characterized by the following properties: compressive (crushing) strength, modulus of rupture (transverse strength), tensile strength, Young's modulus (elasticity in flexure), modulus of rigidity (elasticity in shear), Poisson's ratio $\left(\frac{\text{Young's modulus}}{2\times \text{modulus of rigidity}} - 1\right)$ impact toughness (hardness), scleroscope (bonding) hardness, abrasive hardness, cementing value, grindability, etc.

However, the mechanical results may be largely influenced by moisture condition and the direction into which the sample is analysed. Moreover, they do not give information about the durability of a rock against weathering conditions, e.g. a high resistance of a rock against abrasion may coincide with a low as well as with a high resistance to weathering conditions. The following are examples of chemical, X-ray and differential thermal analyses of various kinds of rocks and gravels and their use in civil and rural engineering constructions under various weathering and other conditions¹).

ROCKS AND GRAVELS USED IN CONSTRUCTIONS

a. Magmatic rocks

Intrusive (plutonic) magmatic rocks (see table 1) which are commonly used for constructional works, e.g. granite, syenite, leucite, nepheline, diorite, gabbro, peridotite (the order being that of increasing basicity)²) are formed by slow cooling of the molten magma. Therefore, they consist of a compact mass mostly composed of close interlocking, well-developed crystals uniform in size with a granular (granitoid) texture. Extrusive (volcanic) magmatic rocks (see table 1) which are also generally used for constructional works, e.g. rhyolite, phonolite, trachyte, dacite, andesite, basalt, diabase, pikrite (the order being that of increasing basicity), have resulted from more rapid cooling. Thus they contain larger crystals embedded in a fine-grained ground mass (felsitic structure).

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¹) The author is indebted to Professor Ir. E. C. W. A. Geuze, Director of the Laboratory of Soil Mechanics, Delft, for critical remarks.

²) Light coloured acidic rocks are chiefly composed of quartz, orthoclase and white mica (muscovite) = ca $> 65\%$ SiO_2. Basic magma have less silica = ca $< 50\%$ SiO_2 and more iron, lime and magnesium minerals (hornblende, augite, hypersthene, magnetite), which give rise to dark coloured types.

Table 1. Rocks and their components

A. Magmatic Rocks

I. Without texture: pitchstone, perlite, obsidian, pumice stone.

II. With texture.

Calcium-alkali group

extrusive (volcanic)	rhyolite	trachyte	dacite	andesite	diabase, basalt	pikrite	
ganganous (intermediate)	granite porphyry (aplite, pegmatite)	syenite porphyry (minette, vogesite)	quartz diorite porphyry	diorite porphyry	gabbro porphyry (odinite)		
intrusive (plutonic)	granite	syenite	quartz diorite	diorite	gabbro, norite	peridotite, pyroxenite	anorthosite
main components	quartz	without quartz	quartz	without quartz			
	K-feldspar Na-feldspar	Na/Ca feldspar with increasing Ca/Na ratio but in decreasing amounts ⟶				without feldspar	Ca-feldspar
	micas, pyroxenes, amphiboles				biotite, pyroxenes, amphiboles		
	without olivine				with and without olivine		

Alkali group

extrusive (volcanic)	quartz keratophyre	alkali trachyte	leucite- and nepheline-phonolite	tephrite		leucite nepheline melilite } basalt	augitite limburgite	trachy dolerite
ganganous (intermediate)	alkali granite porphyry	alkali syenite porphyry	nepheline porphyry					
intrusive (plutonic)	alkali granite	alkali syenite (laurvikite,) monzonite	nepheline and leucite-syenite	shonkinite	theralite	missourite fergusite		essexite
main components	quartz	without quartz						
	orthoclase		orthoclase, leucite, nepheline	leucite/nepheline orthoclase	leucite/nepheline plagioclase	leucite, nepheline melilite		all minerals with the exception of quartz
	mica, Ca- and alkali pyroxenes + ditto amphiboles					biotite, pyroxenes	pyroxenes	
	without olivine			with and without olivine			with olivine	

B. Sedimentary Rocks

a) Mechanical action:

coarse grained:	conglomerate (round particles) breccie (angular particles) graywacke (rounded and angular particles)	siliceous, ferruginous, carbonaceous, kerogenous
medium grained:	sandstone, (siliceous, ferruginous, micaceous, argillaceous, calcareous, glauconitic, feldspathic (arkose), kerogenous)	
fine grained:	mudstone, shale (carbonaceous, argillaceous, ferruginous, bituminous, kerogenous).	

b) Chemical action:

travertine, calcareous tuff, gypsum, anhydrite, carnalite, sylvinite, halite, kieserite, polyhalite, iron banks (concretions), manganese banks (concretions), bauxite, limonite (iron ore), phosphate, flint, chert.

c) Organogenic action:

limestone (coral, foraminiferous, crinoidous, molluscous, öolitic, glauconitic, argillaceous, dolomitic, chalk, marl, diatomaceous, carbonaceous).

C. Metamorphic Rocks

a) Foliated (banded):

light coloured and coarsely laminated	: gneiss	(sericite, biotite, hornblende, garnetiferous, etc.)
dark coloured and finely laminated	: schist	(chlorite, actinolite, hornblende, garnetiferous, amphibolitic, sillimanite, graphite, tourmaline, talc).

b) Non foliated: slate (carbonaceous), phyllite (micaceous), quartzite, marble (white, pink, gray, etc.), dolomitic marble, dolomite, serpentine, hornfels (baked shale formed by volcanic action), soapstone.

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¹) Classification essentially after H. Rosenbusch (Elemente der Gesteinslehre, 4th Ed., 1923 edited by A. Osann, E. Schweizerbartsche Verlagsbuchhandlung, Stuttgart pp. 779) and compiled by B. G. Escher (Algemene Geologie, 6th Ed. 1945, N.V. Wereldbibliotheek, Amsterdam pp. 525. Rosenbusch classified the magmatic rocks on texture and geological association in addition to mineralogical composition. Other classifications are for example of P. Niggli (Die Magmentypen, Schweizerische Mineral. und Petrogr. Mitt., 1936, *16*, 335–399) which is based on chemical composition modified by other considerations and of S. J. Shand (Eruptive rocks, 3th Ed. 1947, Thomas Murby, London pp. 488) which is based on relative excess or deficiency of silica, alumina, sodium potash, lime and the texture of the rocks.

When the molten mass is suddenly chilled by very rapid cooling, a glassy brittle mass (e.g. obsidian) is formed. When the rate of cooling has been intermediate between that in extrusive and that in intrusive rocks, a porphyritic structure results, i.e. many large crystals (phenocrysts) embedded amongst finer crystals. These kinds of rocks (see table 1), e.g. aplite, pegmatite, alkali granite porphyry, syenite porphyry, quartz diorite porphyry, diorite porphyry, gabbro porphyry (the order being that of increasing basicity), which are most generally used in constructional works, are found in gangs or dikes. Molten lava has flown here from the inner magmatic chamber to the outside of the earth's crust.

Magmatic rocks may therefore show from the outer to the centre successively, a glassy, a porphyritic, a felsitic and a granitoid structure, the difference being caused by the different rates of cooling.

Magmatic rocks are very suitable for construction works as they have favourable mechanical properties (see table 2). The coarser plutonic ones are somewhat less tough and less resistant to abrasion (traffic) than the finer-grained volcanic ones, which agrees with the coarser structure of the first and the fine-grained and closely interlocking structure of the latter. However, when these magmatic rocks contain bubbles or are even spongy (due to gases expanding from the molten mass) their strength and abrasive resistance is considerably decreased.

TABLE 2. Mechanical properties of several kinds of rocks as used in civil and rural engineering constructions.

Description	Kind of rocks		
	magmatic	sedimentary[1])	metamorphic[1])
Compressive (crushing) strength ($lb.inch^{-2} \times 10^3$)	35–50	5–30	20–40
Modulus of rupture (transverse strength) ($lb.inch^{-2} \times 10^3$) . . .	3–6	0.7–3	3–6
Tensile strength ($lb.inch^{-2} \times 10^3$) .	1–2	0.1–1.5	0.8–3
Young's modulus (elasticity in flexure) ($lb.inch^{-2} \times 10^{-6}$)	9–12	0.8–9	4–10
Modulus of rigidity (elasticity in shear) ($lb.inch^{-2} \times 10^{-6}$).	2–6	0.3–4	2–6
Impact toughness (cm)	15–30	3–15	10–20
Scleroscope hardness (scleroscope units)	80–110	20–60	50–80
Abrasive hardness (H_D) (revol. × $inch^2 \times 10^{-3}.lb^{-1}$)	25–35	2–15	6–20

See for details e.g. Lord (1916), Jackson (1916), Kessler (1927), Kessler and Sligh (1927, 1932), Kessler et al. (1940), Woolf (1930), Obert et al. (1946), Windes (1949, 1950), Evison (1956).

[1]) Data only of compact types.

Magmatic rocks are furthermore very resistant to weathering; the basic ones, e.g. basalt decomposes faster and also has more binding (cementing) power than the acidic ones, e.g. granite. This characteristic is reflected by their behaviour, against 25% HCl for 1 hour at ca 100 °C (see table 3). Thus 2 to 6% is dissolved in acid rocks against ca 12 to 40% from basic rocks.

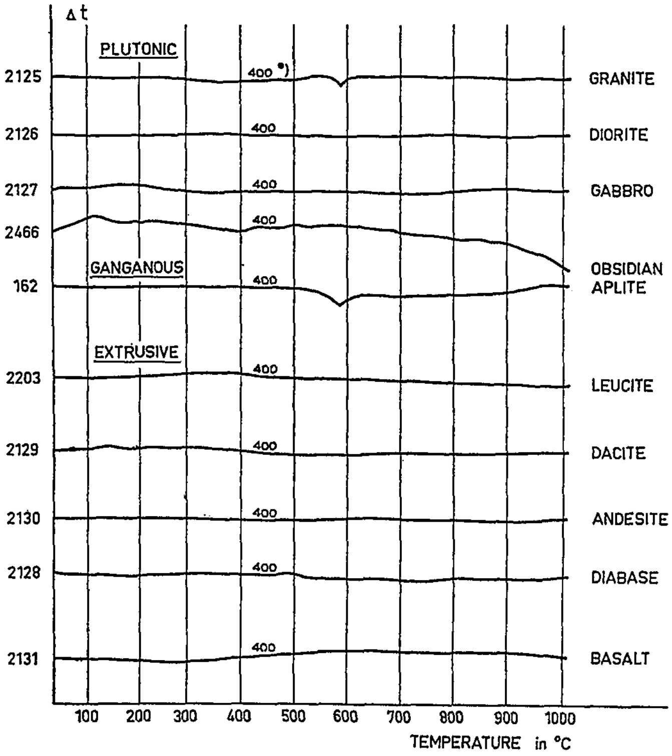
TABLE 3. Elements dissolved (in %) from several kinds of magmatic rocks by extraction with 25% HCl for 1 hour on a boiling water bath

	K_2O	CaO	MgO	Na_2O	Mn_3O_4	Fe_2O_3	Al_2O_3	TiO_2	P_2O_5	SiO_2	Total
I. *Without structure*											
27 Obsidian	tr	tr	0.02	tr	tr	0.46	tr	tr	tr	0.08	0.56
II. *With structure*											
Calcium-alkali group, extrusive											
3 Granite, Georgia	0.04	0.09	0.02	tr	tr	0.20	0.20	0.02	0.07	0.26	0.90
5 Diorite, Massachusetts	0.13	1.07	0.44	0.03	tr	3.72	0.63	0.02	0.47	2.00	8.51
1 Gabbro, Massachusetts	0.18	1.24	0.42	0.02	tr	4.60	0.48	0.05	0.70	2.05	9.74
6 Dacite, San Luis Obispo County	0.22	0.11	0.50	0.03	0.01	2.58	0.54	0.17	0.07	1.84	6.07
4 Diabase, Massachusetts	0.01	1.17	0.08	0.13	tr	4.93	1.84	0.16	0.11	4.25	12.68
2 Basalt, Somerset County	0.02	1.05	1.47	0.16	tr	4.65	2.85	0.08	0.06	8.60	18.94
Alkali group, extrusive											
282 Leucite basalt, Wyoming	6.16	1.68	0.80	0.10	tr	2.13	6.90	0.22	0.68	20.68	39.35

TABLE 4. Elements dissolved (in %) from diabase gravel from a quarry in Curacao by extraction with 25% HCl for 1 hour on a boiling water bath. Furthermore from silicified diabase tuff gravel from another quarry in Curacao

	K_2O	CaO	MgO	Na_2O	Mn_3O_4	Fe_2O_3	Al_2O_3	TiO_2	P_2O_5	SiO_2	Total
11 compact >1 mm.	0.01	2.28	5.40	0.07	0.02	5.40	5.50	0.12	0.05	12.75	31.60
12 soft >1 mm.	0.02	2.10	6.75	0.06	0.02	7.79	6.85	0.31	0.04	20.58	44.52
1332 soft <1 mm.	0.02	3.58	6.98	0.05	0.04	7.90	7.32	0.06	0.03	23.30	49.28
7721/31 silicified diabase tuff	0.01	0.82	1.70	0.07	0.02	4.05	2.65	0.14	0.11	8.80	18.37

Furthermore, their differential thermal analyses (d.t.a.) curves1) show straight lines to 1000 °C (see figure 1) on account of lack of secondary minerals with O H groups. The latter are formed by decomposition of primary magmatic minerals.



*) Weight of dried (1 hour at 105 °C) sample in mg

Fig. 1.
D.t.a. of some magmatic rocks

An exception are rocks which contain large amounts of quartz (25–35%) e.g. granite, rhyolite, pegmatite, aplite, quartz-porphyry, etc., which have a sharp but small thermal effect at 573° (see figure 1). This results from the reversible inversion of α-quartz (low quartz with trigonal symmetry) to β-quartz (high quartz with hexagonal symmetry).

This sharp inversion reaction is used by several authors, e.g. Faust (1948) and Barshad (1952), to obtain a calibration point for the temperature scale in the d.t.a. Thus according to Tuttle (1949), quartz of various origin showed only a variation of 0.60 °C above and 1.30 °C below the standard inversion temperature of 573.3 ± 0.1 °C.

Plate I, figure 2 and table 4 show the X-ray, d.t.a. and chemical analyses, respectively of coarse diabase gravel which was previously cleaned by washing with water and fine $<$ 1 mm diabase particles with adhering weathering products both sampled from the same quarry of diabase rock which was explored near Willemstad (Curaçao) for the platform of an airfield. They show that the diabase gravel has been largely weathered – see the greater

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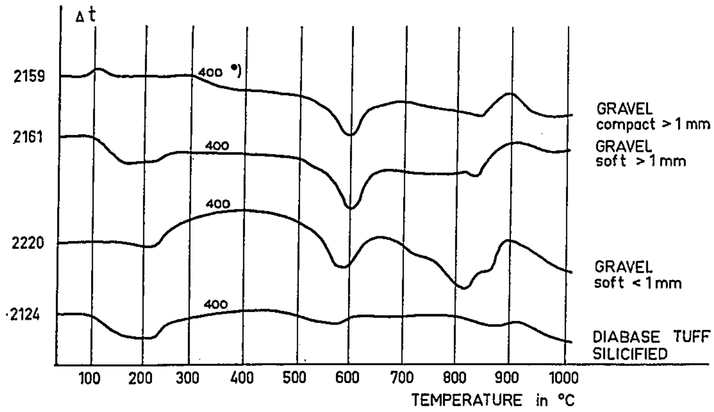
1) All the d.t.a. tests described in this article have been performed with the equipment constructed and described by De Bruyn (1954).

amounts for total substance dissolved by 25% HCl at ca 100 °C and the greater thermal effects at the d.t.a. as compared with that of unweathered diabase rock (see table 3 and figure 1). Consequently, the gravel which is sampled in this quarry should first be washed and sieved and only the coarser ones ($>$ 1.5 inch) should be used for constructive purposes, i.e. where great resistance to mechanical and weathering forces are needed for years without interruption for repairs.

The silicified diabase tuff, which can easily be distinguished by X-ray and differential thermal analysis from the foregoing samples (see plate I and fig. 2) is very resistant (see table 4) and therefore the most suitable.



*) Weight of dried (1 hour at 105 °C) sample in mg

Fig. 2.
D.t.a. of some samples of diabase gravel from a quarry at Curacao and of silicified diabase tuff from another quarry at Curacao

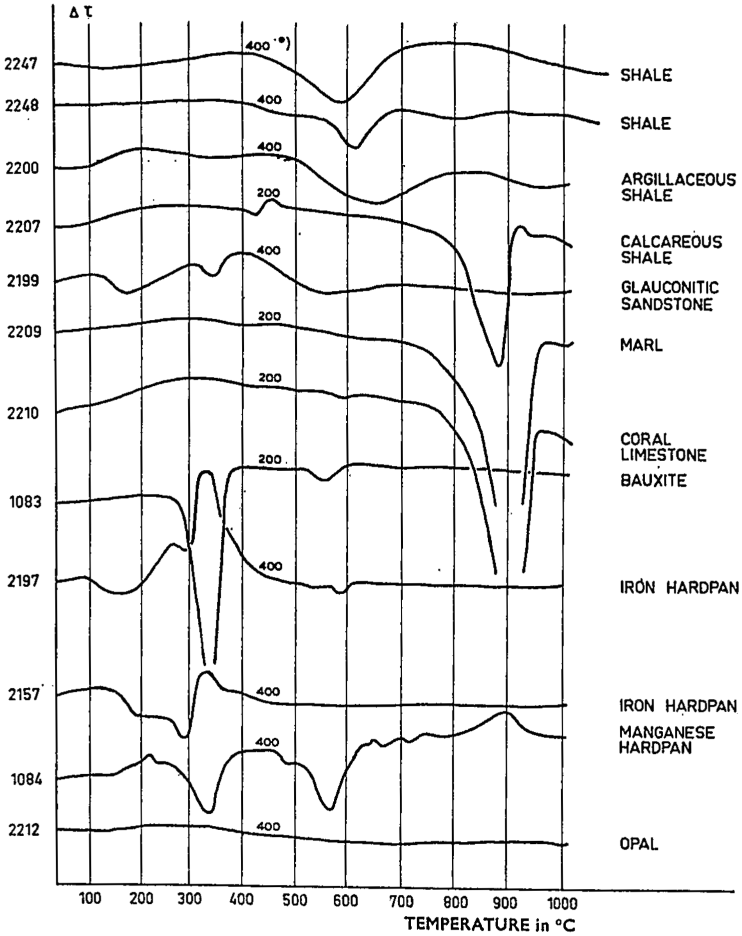
b. Sedimentary rocks

Rocks belonging to this group (see table 1) which can be employed for constructional purposes (e.g. conglomerate, breccie, sandstone, tuff, marl, chalk, limestone, shale), are derived from debris of other rocks on account of wind, water, gravity, chemical and organogenic action.

By sedimentation the heavier and coarser fragments are sorted from the lighter and finer ones and stratified rocks result. They have all gradations of fineness, i.e. ranging from soft and friable to compact and hard. The coherence is due to the amount of clay which is included or to the kind and amount of cement (siliceous, calcareous, ferruginous, manganous, aluminous), by which the separate particles are held together. Hardpans in soils which may cover large areas result from percolating water carrying colloidal weathering products to a lower level. There these colloids are flocculated by electrolytic action and soil particles are included. A coherent mass (ferruginous, manganous, aluminous, calcareous) results which, when dry, may be very hard and resistant e.g. crystallites of iron and manganous oxides formed from amorphous hydroxides, cement the particles together. Hardpans may also result in hot dry seasons from the escape of CO_2 from capillary water containing dissolved iron or manganese-hydrocarbonates or from evaporation of capillary water with dissolved weathering products. Also in this case a compact mass is formed at a certain depth beneath the soil surface. Finally hardpans may be formed through the action of iron and manganese bacteria, e.g. Leptothrix ochracea, Bacillus circulans, Bacillus polymyxa – see Leeper and Swaby (1940), Roberts (1947), Baars (1950), Bromfield (1954) – when sufficient easily decomposable nutritive organic matter (humus) occurs.

Mechanical strength of sedimentary rocks varies considerably. From nearly zero to amounts as mentioned in table 2 may be found for the more compact types.

Figure 3 shows the d.t.a. diagrams, table 5 the chemical and plate II the X-ray analyses of several sedimentary rocks. They show that with the exception of sandstone, shale and opal all have strong endo- (and exo-) thermal reactions and that, with a further exception of bauxite, large amounts of material are dissolved when the samples are treated with 25% HCl for 1 hour on a boiling waterbath. Chalk and limestone even effervesce at room temperature when treated with diluted acid, e.g. 1% HCl.



*) Weight of dried (1 hour at 105 °C) sample in mg

Fig. 3.
D.t.a. of some sedimentary rocks

Table 5. Elements dissolved (in %) from several kinds of sedimentary rocks with 25% HCl for 1 hour on a boiling water bath

		K_2O	CaO	MgO	Na_2O	Mn_3O_4	Fe_2O_3	Al_2O_3	TiO_2	P_2O_5	SiO_2	Total
13	argillaceous shale, U.S.A.	0.28	1.08	1.05	0.02	0.01	1.97	1.71	0.02	0.15	2.50	8.79
W–2	argillaceous shale, The Netherlands	0.04	1.19	0.96	0.05	0.03	8.15	1.25	0.02	0.05	6.26	18.00
984	iron hardpan, ditto	tr	0.35	0.22	tr	0.04	25.70	0.41	0.06	1.43	2.48	30.69
676	iron hardpan, ditto	tr	tr	0.08	tr	0.09	51.54	3.35	0.18	0.05	1.35	56.64
M	manganese iron hardpan, Sumatra	tr	0.3	tr	tr	17.1	13.6	9,8		tr	6.8	47.6
171	bauxite (red), Surinam	tr	tr	tr	tr	tr	7.20	6.93	0.08	0.02	0.04	14.27
985	bauxite (white), ditto	tr	0.03	0.02	tr	tr	0.17	8.36	0.02	tr	tr	8.60
170	bauxite (red), Bintan Island (Indonesia)	0.01	0.01	tr	tr	tr	6.88	4.29	0.08	tr	0.04	11.31

Table 6. Elements dissolved (in %) from several kinds of metamorphic rocks by extraction with 25% HCl for 1 hour on a boiling water bath

		K_2O	CaO	MgO	Na_2O	Mn_3O_4	Fe_2O_3	Al_2O_3	TiO_2	SiO_2	P_2O_5	Total
273	black slate, The Netherlands . . .	0.10	0.28	0.63	0.09	0.04	2.89	1.56	0.01	1.55	0.06	7.21
H–5	gray pyritic slate, ditto	0.03	0.96	2.48	0.04	0.02	24.30	3.55	0.04	0.68	0.01	32.11
215	gray slate, Belgium	0.01	0.02	0.66	tr	tr	4.96	2.04	0.02	2.08	0.04	9.83
1001	phyllite, Luxemburg	0.02	0.07	0.26	tr	tr	2.91	1.09	0.03	1.05	0.08	5.51
26	sericite schist, Silesia	0.03	1.21	0.13	tr	tr	0.35	1.19	tr	0.09	tr	3.00
25	paragonite schist, Vermont. . . .	0.12	0.30	0.27	0.02	tr	2.03	0.89	0.05	0.80	0.10	4.58
22	actinolite schist, California	tr	0.47	1.14	tr	tr	1.43	1.27	0.08	1.86	0.14	6.39
21	biotite gneiss, Massachusetts . . .	0.90	0.29	0.62	tr	tr	3.91	1.72	0.26	3.98	0.15	11.83
24	soapstone, Virginia	tr	3.20	5.05	tr	0.02	3.70	1.83	0.09	2.78	0.03	16.70
966	serpentine, Celebes	tr	tr	9.68	tr	0.03	5.05	0.49	0.03	17.50	tr	32.78
967	serpentine, Moravia.	tr	0.01	8.35	tr	0.04	4.83	0.86	0.03	20.82	tr	34.94

Table 7. Elements dissolved (in %) from weathered serpentine rock from a quarry near Havana by extraction with 25% HCl for 1 hour on a boiling water bath. Furthermore of antigorite and chrysotile

		K_2O	CaO	MgO	Na_2O	Mn_3O_4	Fe_2O_3	Al_2O_3	TiO_2	SiO_2	P_2O_5	Total
	Weathered serpentine, Havana . . .	tr	0.43	22.85	tr	0.03	6.71	0.70	0.03	30.66	tr	61.41
	Weathered serpentine, Havana . . .	tr	1.99	21.10	0.01	0.02	8.25	1.46	0.04	31.85	tr	64.72
756	antigorite, Pennsylvania.	tr	0.03	8.35	tr	tr	2.01	0.29	0.02	10.30	tr	21.00
918	chrysotile, Saxony	tr	0.07	28.05	tr	0.06	2.86	1.59	0.04	27.60	tr	60.27

Also, under natural conditions iron and manganese hardpans are not very resistant to weathering. Thus, when used for road constructions in the tropics with heavy rainfalls they will last only for some 5 years. Bauxite, which mostly consists of hydrargillite $Al(OH)_3$, is more resistant to weathering than the iron and manganese hydroxide and oxide concretions.

Yet, the application of all this material, i.e. hardened tuffs, (loose, ejected volcanic material cemented by silicic acid) may still be economical in regions where resistant rocks are lacking or where they can only be obtained from other regions at high cost.

Sandstone and shales (mud stones) are formed from material that has already resist weathering processes and therefore they only contain very resistant minerals like quartz, illite + kaolinite, respectively. The cementing value of both these rocks e.g. in macadam roads is of course practically nil, as they do not provide appreciable amounts of binding cement (sesquihydroxides and silicic acid) when weathering.

c. Metamorphic rocks

The rocks and gravels belonging to this group (see table 1) which are of importance for constructional works, e.g. gneiss, schist, amphibolite, slate, quartzite, marble, have resulted from the metamorphism of magmatic or sedimentary rocks, on account of hydrothermal action, high pressure, high temperature, gases and fluid action.

Metamorphism may be slight or it may be so radical that the original rock cannot be accurately identified. Metamorphic rocks derived from clays which have withstood high pressures, are mostly very hard but have a slaty cleavage. It is due to the parallel alignment of minute mica flakes rectangular to the pressure direction, which gives the surface a dull silvery appearance.

When the metamorphosis has been more vigorous, many new (secondary) minerals (sericite, chlorite, tourmaline, garnet, epidot) are formed in parallel layers, which results in a banded (foliated) structure (gneiss, schist). All these rocks, even those very resistant to weathering (e.g. some types of slates) are less suitable for civil and rural engineering purposes as they are apt to split. Some types of slates with extreme hardness and perfect cleavage (phyllites), however, are used for roofing.

Mechanical properties of these kinds of rocks naturally vary considerably in the direction perpendicular and parallel to the plane of stratification.

Metamorphism of shales and slates caused by contact with molten lava gives rise to baked, very resistant rocks = horn rock (horn fels). However, they are mostly folded through volcanic action and therefore less suited to constructional purposes as they contain many fissures.

The mechanical properties of metamorphic rocks with a compact, not folded or foliated structure, such as some types of slates, marble, dolomite, quartzite and serpentine are mentioned in table 2.

Figure 4, table 6 and plate III show the d.t.a., chemical and X-ray analyses of several kinds of metamorphic rocks. They show that slates, schists and gneiss, which are very resistant to HCl, have only a small thermal reaction. On the other hand, serpentine which looses to 50% of its constituents when treated with 25% HCl and marble and dolomite which are even wholly dissolved, have a large thermal reaction. Also in nature marble, dolomite and serpentine rocks have, under the same conditions of weathering deeper profiles overlying the bedrock than slate – and quartzite rocks. The

Plate I.

X-ray photographs of diabase samples from a quarry at Curaçao and of unweathered diabase rock from Massachusetts. Furthermore of silicified diabase tuff from another quarry at Curaçao.

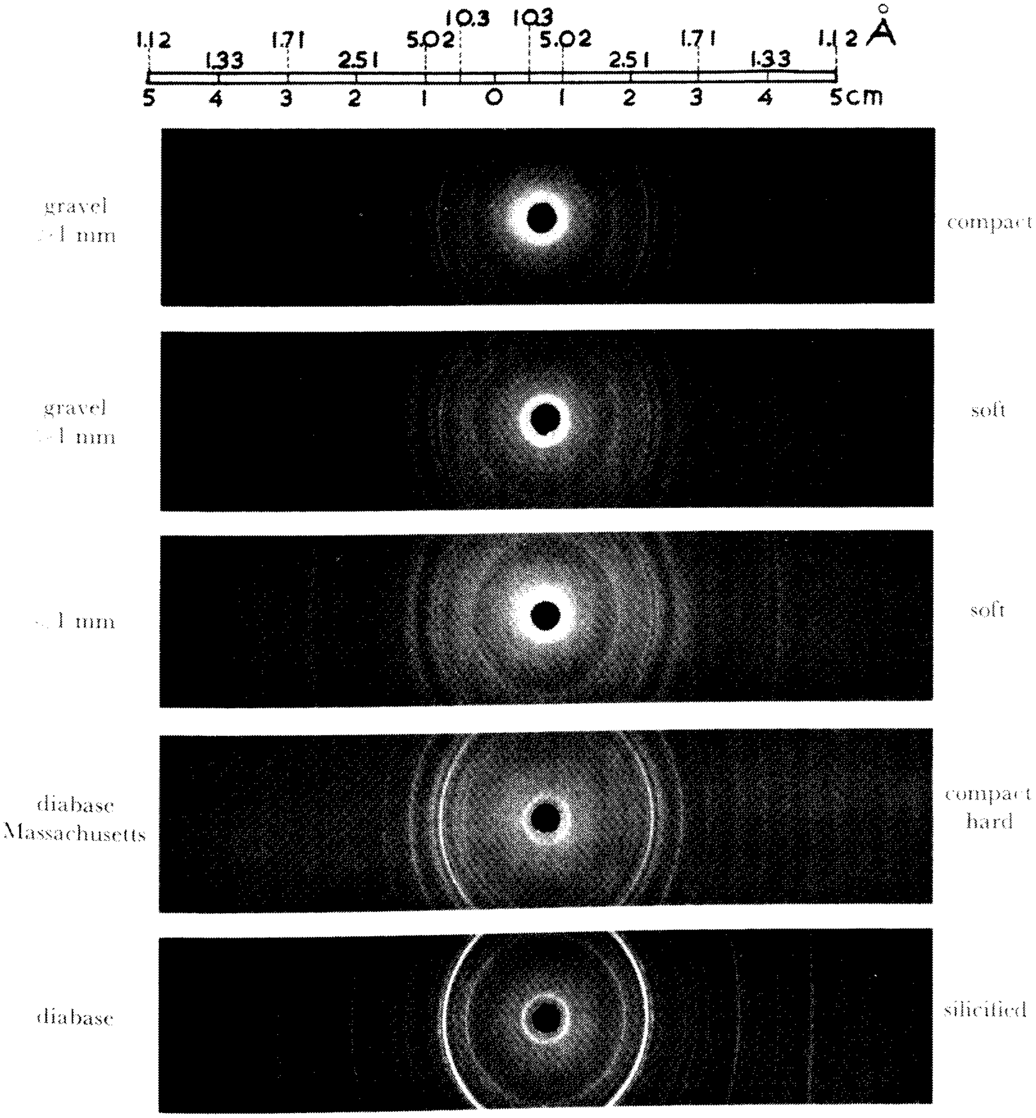


Plate II. X-ray photographs of magmatic and sedimentary rocks.

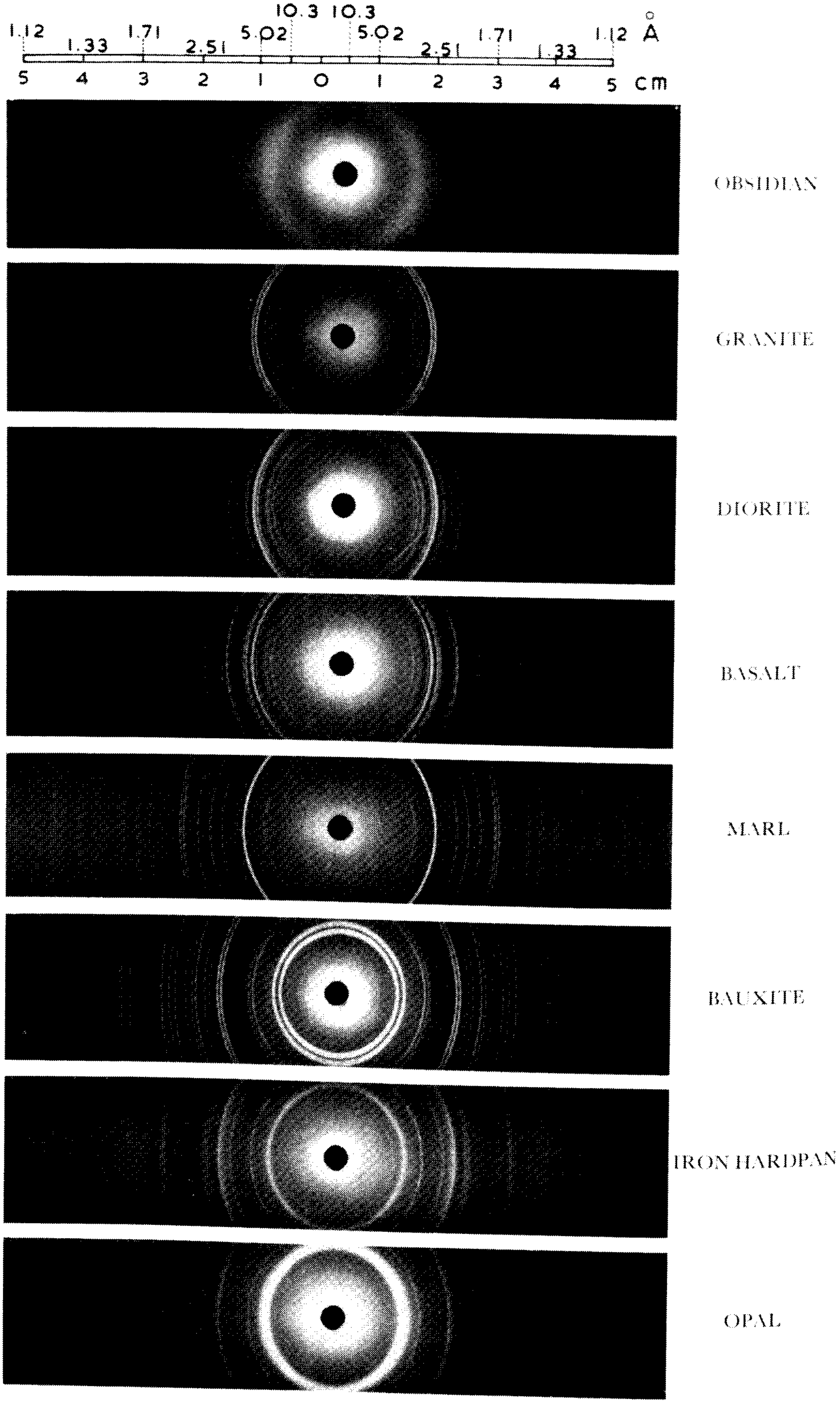


Plate III. X-ray photographs of metamorphic rocks.

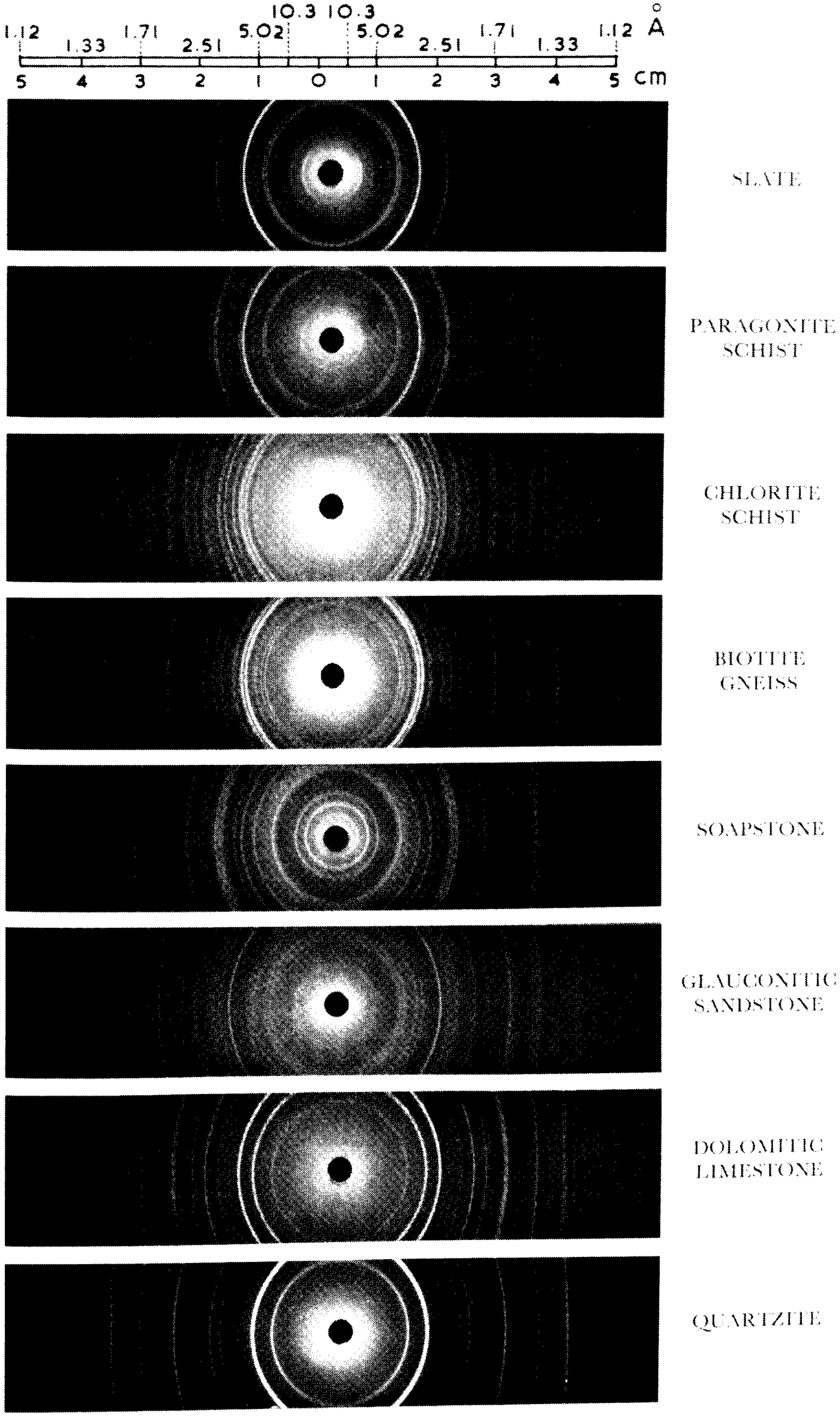


Plate IV.
X-ray photographs of weathered serpentine rock and its white weathering product from a quarry at Havana. Furthermore of serpentine, antigorite and chrysotile.

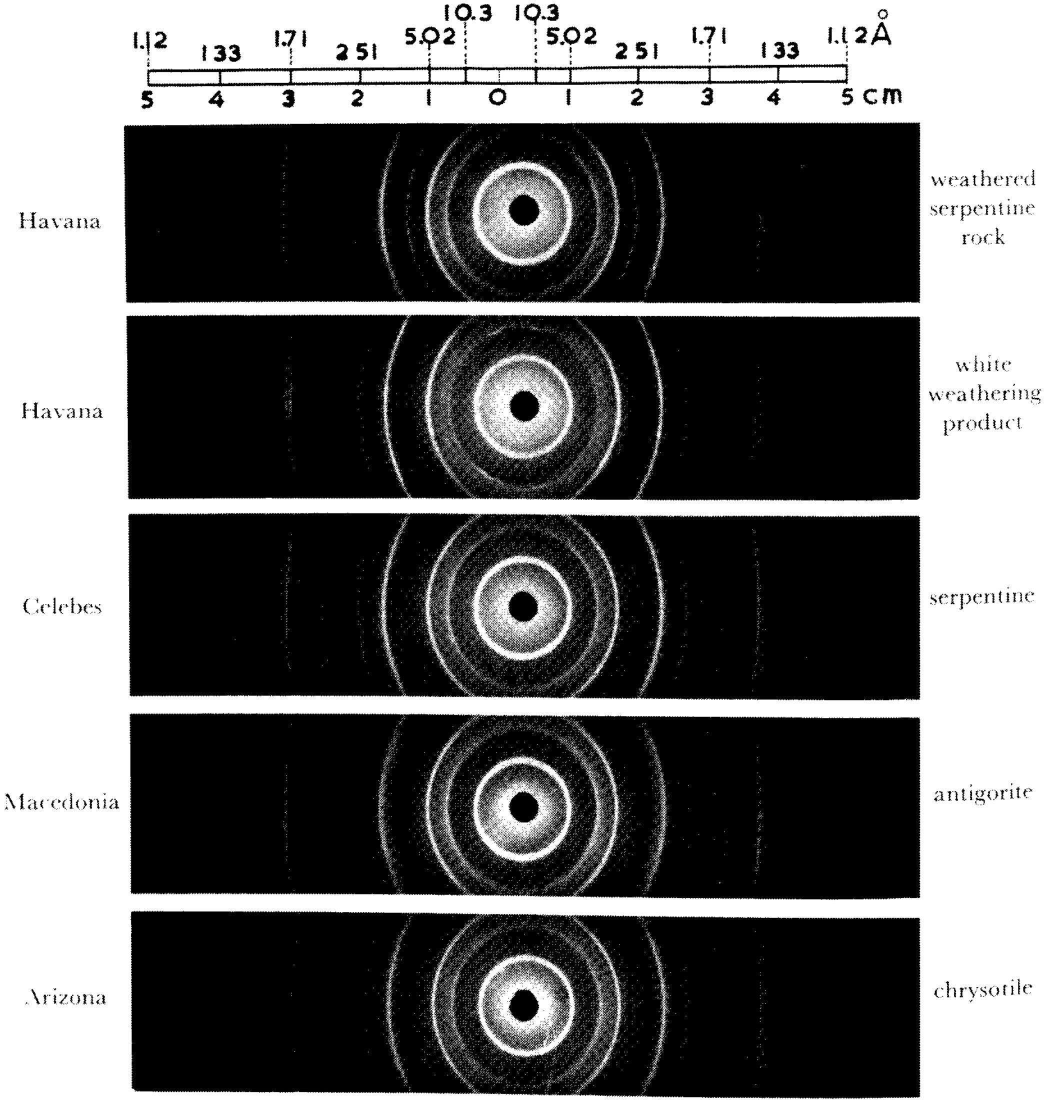
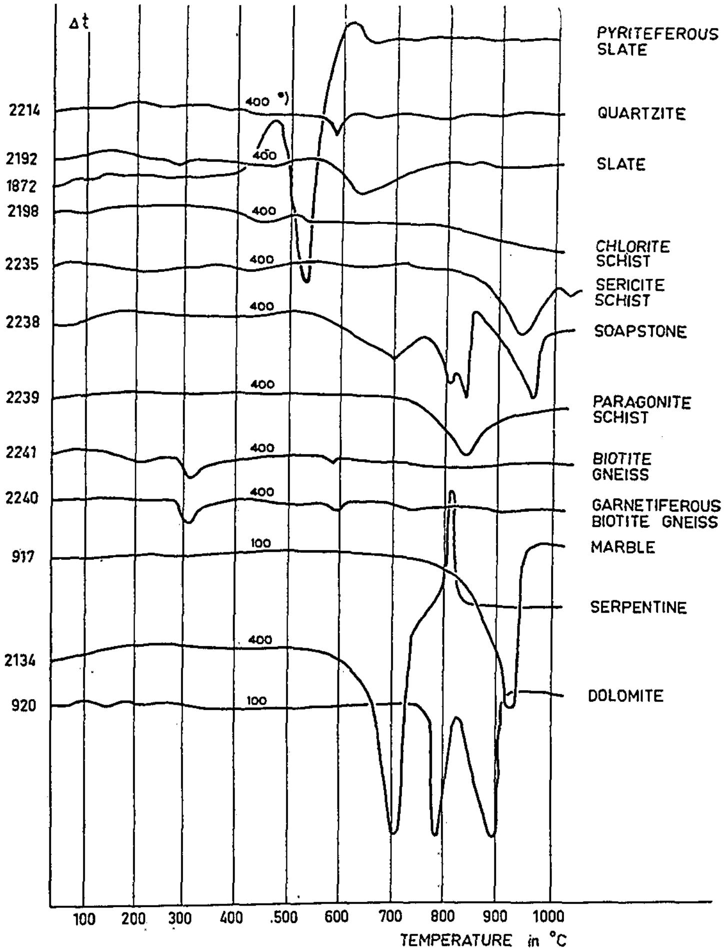


Fig. 4.
D.t.a. of some metamorphic rocks



*) Weight of dried (1 hour at 105 °C) sample in mg

latter rock resulted from a filling up of the pores of sandstones by silicic acid gel, which afterwards hardened (crystallized) under pressure. The cement can even in this case be so firm, that the rock breaks across the original sand particles rather than around them. The extreme hardness of quartzites may in spite of their extremely great resistance to mechanical forces prevent them from being used for constructions.

Of all the above named compact rocks, serpentine rocks are still the most suitable for outwork constructions. They result from metamorphism of ultrabasic rocks (peridotite) and they contain antigorite and chrysotile. Both minerals are a high graded Mg-silicate mineral (ca 30 to 40% MgO), the former being the earthy and the latter the fibrous variety.

However, strongly weathered serpentine rock, e.g. as found in a quarry in the vicinity of Havana (Cuba) has only a compressive strength varying from 400 to 830 kg cm^{-1},1) which is caused by the presence of cracks filled with a

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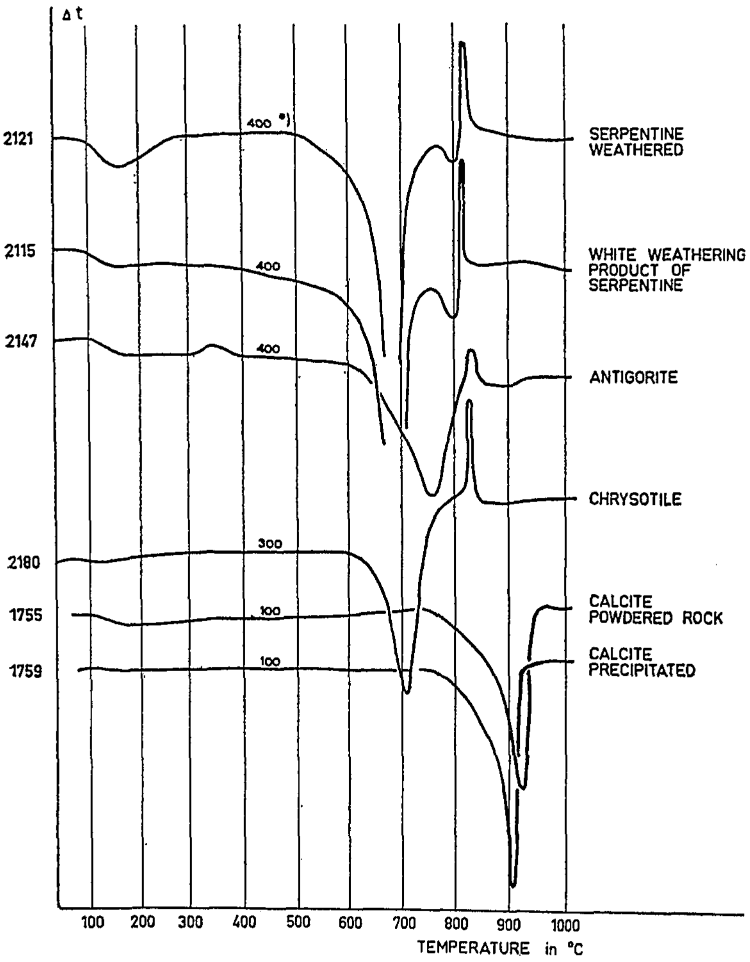
1) Analysed by: Instituut voor Bodemmaterialen en Bouwconstructies, Delft, Netherlands.

black coated (high Mn-graded) mass. This strongly weathered rock has large endo- and exothermal effects in its d.t.a. diagrams (see figure 5) which are caused by chrysotile and some antigorite (see also plate IV). The thermal effects are smaller for the compact serpentine rock than for the soft desintegrated serpentine (see figures 4 and 5). It is caused by the increased pressure of the H_2O vapour escaping from the more compact unweathered particles, thus increasing the temperature and consequently the entropy of the H_2O molecules and by which the thermal effect of the reaction is decreased. For the same reason the thermal effect of very fine precipitated calcite is also larger than that of coarse calcite (see figure 5).1)



*) Weight of dried (1 hour at 105 °C) sample in mg

Fig. 5.
D.t.a. of weathered serpentine from a quarry at Havana.
Furthermore of antigorite, chrysotile and of coarse and fine calcite.

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1) A decrease in particle size, however, not always coincides with a larger thermal effect at a d.t.a. For example, the heat of formation (ΔH^0) of carbon dioxide from diamond is larger than that from fine graphite = –94.507 and –94.052 kcal mole^{-1}, respectively and therefore the exothermal effect in the d.t.a. is also larger for the first reaction. Another example is that very fine quartz and kaolinite particles with a pronounced disordered layer (Beilby layer) on their surface (and therefore with less active mass per unit weight) have a smaller thermal effect than the coarser ones.

By heating with 25% HCl for 1 hour at 100 °C, 33% and 64% were dissolved from the unweathered compact serpentine rock and the soft thoroughly weathered serpentine, respectively (see tables 6 and 7). Consequently the weathered serpentine is far less resistant to weathering action under equal conditions than the unweathered serpentine.

Marble is very suitable for monuments which require a rock which, although somewhat less resistant than serpentine or basic igneous rocks does not stain during the weathering process.

WEATHERING OF ROCKS AND GRAVELS

Water is one of the most predominant weathering agents. Thus when rocks are immersed in water or when water is condensed on rocks cooler than the surrounding air, they will hydrolyse and the pH of the water will increase (e.g. marble) or decrease (e.g. gypsum). The reaction will proceed until an equilibrium is attained. Weathering leads to a decrease in the free energy of formation $= \triangle F^\circ$ ($\triangle F^\circ = \triangle H^\circ - T\triangle S^\circ$ in which T = temperature in °Kelvin and S = entropy).

According to Keller (1954) there exists a close direct relation between the rate of weathering of minerals and their heats of formation ($\triangle H^\circ$). The latter can be used instead of $\triangle F^\circ$ because in this case differences between the entropy of the various compounds are only small. Thus olivine is more susceptible to weathering than pyroxene.

Furthermore magnesite ($MgCO_3$) rock, with $\triangle H^\circ = -266$ kcal. mole^{-1} and with a solubility product (K) $= 2 \times 10^{-4}$ at 298°K (25 °C), will under equal conditions dissolve better than limestone or marble ($CaCO_3$) rock with $\triangle H^\circ = -288$ kcal. mole^{-1} and with a solubility product $= 1.2 \times 10^{-8}$ at the same temperature. However, dolomite ($CaMg(CO_3)_2$) rock with $\triangle H^\circ = -556$ kcal. mole^{-1} will be far more insoluble than $CaCO_3$ or $MgCO_3$ rock.

The relation between the activity product (K′) of a slightly soluble salt and the free energy of its equilibrium reaction ($\triangle F^\circ$) is as follows:

$$K' = \frac{f^{+}\text{ c-cation} \times f^{-}\text{ c-anion}}{\text{c salt}} = f^{+} f^{-} K$$

$$\triangle F^\circ = -RT \ln K' = -RT \ln f^{+} f^{-} K$$

in which: f^{+} and f^{-} are activity constants

K = c-cation.c-anion = solubility product (c salt is a constant)

R = the gas constant = 1.986 g cal deg.$^{-1}$ mole^{-1}

T = absolute temperature (°Kelvin)

The activity coefficient of an ion in a solution depends on its nature, and its valency; furthermore on the activity of the other ions in the liquid and on the dielectric constant (ε) of the solution.

The rate at which reaction products of the rocks are removed (e.g. by flowing water) or are dissolved by other agents in the water (e.g. sesquihydroxides by acids and silicic acid by alkalis) is another factor by which the weathering of rocks by hydrolysis is influenced.

Reaction rate increases with temperature ca 10 to 20% for each rise of

1 °C. It is caused only to some extent by increased collisions and largely by the increase of activated ions.

The relation between reaction rate and temperature can be represented by the Van 't Hoff – Arrhenius equation:

$$\frac{d \ln k}{dT} = \frac{E^+}{RT^2}, \text{ which becomes in its integrated form: } k = k_o e^{-\frac{E^+}{RT}}$$

k = reaction rate caused by effective collisions;
k_o = a constant = the reaction rate if all collisions are effective;
E^+ = activated (excess) energy above the average energy properly located in the ions.

The velocity constant of heterogeneous reactions is also increased by speed of stirring (motion); Hixson (1944) found the relation: $k = \alpha(N)^\beta$ in which k is the reaction rate at a certain temperature, N = the rate of stirring and α and β are constants.

Reaction rate also largely depends on the extent of the surface which is in contact with the weathering agents. Thus porous rocks or fine gravel will weather at a faster rate than compact rocks or coarse gravel. Consequently compact heavy limestone (bulk density of limestone and basalt = ca 2.8 to 3.0 and ca 2.6 to 2.8 respectively), although it will be slightly dissolved by diluted HCl, may be used in constructions where acid water or acid vapours are absent, e.g. for the outer cover of sea walls. It should, however, not be used in acid peats, where an acid resistant rock, although somewhat porous, is to be preferred.

Another dominant agent in the weathering process is oxygen. Oxidation of rocks is caused by the free energy of the several elements of the rocks being lower in the oxidized state than in the original one. The process which predominates, is the one in which the greatest loss is obtained.

The rate of an oxidation process primarily depends on the amount of oxygen present in the system. The atmosphere contains 15 to 20 × as much oxygen as water at the same temperature. When temperature or the amount of electrolytes in the water increases, the amount of oxygen decreases considerably.[1])

Another factor is the rate in which the free energy of the system can be lowered. Thus, aluminium is much faster oxidized ($\triangle F^\circ$ Al_2O_3 = –376.77 kcal. mole.$^{-1}$) than iron ($\triangle F^\circ$ Fe_2O_3 = –177.1 kcal. mole.$^{-1}$).

Weathering of rocks is also increased by acids, e.g. sulphuric acid is formed to even a normality of 1 N by oxidation of iron sulphide in soils by bacterial action (genus Thiobacillus). The process is accelerated by flowing water which carries oxygen to the bacteria.

Humic acids are formed in peats under anaerobic conditions and they corrode (bleach) the underlying bed rock considerably. Podzols, which are well-known for their deficiency in plant nutrients are the result of this action. But also very weak acids, e.g. carbon dioxide acid, are destructive at high

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[1]) Fresh water of 0 °C, in contact with oxygen of the air, contains 14.62 ppm oxygen as against 7.67 ppm oxygen at 30 °C. Sea water with a chlorinity (total amount of Cl, Br and J in ppm, assuming that the Br and the J have been replaced by Cl) of 20% contains only 11.00 ppm oxygen at 0 °C and merely 5.37 ppm oxygen at 30 °C (see for further details Fox, 1907).

temperatures in the long run because the H^+ions have a high ionic potential $\left(\frac{\text{charge}}{\text{size}}\right)$ and thus they can diffuse easily through the solution or penetrate into the crystals.[1] In this way under tropical conditions carbon dioxide in rain water to an amount of only ca 5–10 ppm can break down resistant magmatic rocks to 25 m deep layers of thoroughly weathered material which consist mainly of bauxite $\{(Al\ (OH)_3$ and $AlOOH)\}$ mixed with iron hydroxide (FeOOH) and iron oxide (Fe_2O_3) = goethite (limonite) and hematite respectively.

By bacterial action ca 5 to 8 m^3 CO_2 per ha is formed in one year in common soils of temperate climates. In forest and garden soils 5 times as much may be produced.

Water flowing in regions with carbonaceous rocks gives rise to caverns in which the well-known stalactites and stalagmites are found. The reactions involved may be represented as follows:

$$H_2O + CO_2 \leftrightarrows H_2CO_3$$

$$\text{or } K_1' = \frac{fH_2CO_3\,cH_2CO_3}{fH_2O\,cH_2O\,fCO_2\,cCO_2} \text{ or } \frac{fH_2CO_3\,cH_2CO_3}{PCO_2} =$$

$$= K_1' fH_2O\,cH_2O\ CfCO_2 = K_1.$$

$$H_2CO_3 \leftrightarrows H^+ + HCO_3^+ \quad \text{or } K_2 = \frac{fH\ cH.fHCO_3\,c\,HCO_3}{f\,H_2CO_3\,c\,H_2CO_3}$$

$$HCO_3 \leftrightarrows H^+ + CO_3^{--} \quad \text{or } K_3 = \frac{fH\ cH.f\,CO_3\,c\,CO_3}{f\,HCO_3\,c\,HCO_3}$$

$$\underset{\text{(solid)}}{CaCO_3} \leftrightarrows \underset{\text{(dissolved)}}{CaCO_3} \leftrightarrows \underset{\text{(solution)}}{Ca^{++} + CO_3^{--}}$$

$$\text{or } K_4' = \frac{f\,Ca\ c\ Ca\ f\,CO_3\ c\ CO_3}{f\,CaCO_3\ c\ CaCO_3} \quad \text{or } f\,Ca\ c\ Ca\ f\,CO_3\ c\ CO_3 =$$

$$= K_4'\ f\,CaCO_3\ c\ CaCO_3 = K_4$$

From the above results:

$$\frac{K_4}{K_1\,K_2\,K_3} = \frac{f\,Ca\ c\ Ca\ \ P\,CO_2}{(fH\ cH)^2}$$

$$\text{or } \frac{f\,Ca\ c\ Ca\ \ P\,CO_2}{(fH\ cH)^2} = \frac{K_4}{K_1\,K_2\,K_3} = K.$$

($f\,CO_2 = f\,H_2O = 1$; $c\,H_2O$, $c\,CaCO_3$ are constants; $c\,CO_2 = CPCO_2$ where C = Henry's law constant and PCO_2 = partial pressure in atm.)

Consequently, the reactions which give rise to solution and precipitation of $CaCO_3$ when in contact with water depend on three variables:

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[1] Ion velocity at infinite dilution at 18 °C in cm $Volt^{-1} sec.^{-1} \times 10^{-4}$:
$OH^- = 18.0$; $Cl^- = 6.8$; $\frac{1}{2}\,SO_4^{--} = 7.0$; $\frac{1}{2}\,CO_3^{--} = 6.2$
$H^+ = 32.7$; $K^+ = 6.6$; $\frac{1}{2}\,Ca^{++} = 5.3$; $\frac{1}{2}\,Mg^{++} = 4.6$

a. the activity and concentration of the Ca-ions in the liquid, which depends on temperature, amount and nature (valency) of other ions in the same liquid;

b. the partial pressure of free CO_2 in the liquid which depends on temperature and other gases in the same liquid;

c. the activity and the concentration of the H-ions in the liquid which depends on temperature, amount and nature (valency) of other ions in the same liquid.

Thus, if the concentration (pressure) of CO_2 increases and therefore also that of the H ions, the concentration of Ca in the solution will increase. (After the last equation K can only remain constant if the concentration of Ca increases as the concentration of the H ions stands in the denominator; even in its second power.)

Conversely, if the concentration of the H ions decreases, and therefore that of the CO_2 concentration (pressure) also, K can only remain constant if the concentration of calcium ions in the liquid decreases; calcium therefore must precipitate as $CaCO_3$.

After the observations of Wattenberg and Timmermann (1938) the solubility (ionic)product of $CaCO_3$ in water at 20 °C, being 5×10^{-9}, increases to 2660×10^{-9} in sea water at the same temperature, i.e. the latter is about 500 times larger. This phenomenon is caused by the reduced activity of the Ca and CO_3 ions in sea water on account of its larger content of other ions and the product of the active Ca and CO_3 ions (not of the dissolved Ca and CO_3 ions) in the sea water, being a constant value. Consequently, carbonaceous rocks will be more easily attacked by sea water than by fresh water, which contains only a small amount of electrolytes.

Furthermore, in colder climates more $CaCO_3$ rock will be dissolved than in warmer climates, as in the former case more CO_2 can be dissolved in the water than in the latter, e.g. solubility of CO_2 in water at 0 °C = 17.15 ml/l and at 24 °C = 7.82 ml/l (see Buck et al., 1932).

In hot arid regions temperature divergencies to about 40 °C between day and night cause mechanical desintegration of the rocks. The coarser and darker coloured rocks are more affected than the corresponding finer and lighter coloured ones. A primitive manipulation to break large rocks is to heat them first and then to cool them suddenly by water.

Through frost action water in the capillaries of porous rocks (porosity of limestone and sandstones = to 20–30%) expands to 9% of its volume, thereby exerting a pressure of about 2000 lbs. inch^{-2}.¹) Its heat of crystallization at atmospheric pressure is ca 80 cal/gram, which is equivalent to ca 34 kg mtr/gram. The effectiveness of frost action is best illustrated by Cleopatra's Needle. The inscription of this obelisk which had for centuries withstood the weathering action in the hot climate of Egypt, when removed

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¹) If n = the porosity and t_s = the tensile stress in a rock in the equilibrium state when all the water in the pores of the rock has become ice, the following relation exists (see Kessler and Sligh, 1927):

$$2000 = \frac{(1-n)\,t_s}{n} \text{ or } t_s = \frac{2000\,n}{1-n}$$

In this way a rather porous sandstone of ca 25% porosity may be subjected to a disrupting force of 667 lbs. inch^{-2}. High elasticity and high permeability of the rock, however, will decrease the internal stress considerably.

to London was soon damaged and had to be protected by paraffin-waxes, i.e. water detergent aliphatic molecules. (see Schaffer, 1932).

The effectiveness of these detergents has been increased by the introduction of a positive charge which is opposite to that of the mostly negative charge on the surface of clay and rock particles. Consequently, positively activated paraffin-waxes, e.g. Estarfin (Stockhausen & Co, Krefeld), Perlit (Bayer, Leverkusen), Resistol (Scholten, Foxhol) are tenaciously bound by the material which is to be protected.

Silicones, although more expensive, may also be used, e.g. B 50 (Bayer, Leverkusen), MS 10 (Wocker Chemie, München), Rhodorsil 50K (Rhone-Pouleng, Paris), Drisil (Midland Silicones, London) for protection – see for details e.g. Essen-Kray et al. (1954).

Furthermore large organic compounds with strong hydrophobic groups (alkyl or phenyl) and of a cationic nature, e.g. D.D.A.C. (Armour, Welmington) and $(C_2H_5)_2NH_2^+ Cl^-$, respectively.

In recent years the high cost of labour, transport and materials has largely stimulated the use of all these additives to protect buildings and roads against the destructive action of water and frost.

Mechanical desintegration is also caused by chemical action. In this way SO_4^{--} ions formed by oxidation of pyrite and marcasite, which minerals are commonly found in slates, may react with minute particles of calcite, a mineral which may also occur in the slate. As a result, when the material has dried up, $CaSO_4 . 2H_2O$ (gypsum) is formed which has a volume twice as large as that of the original slate. The expansion causes "scaling" of the slate which is a very destructive process, especially for slates which are used for roofing (see Kessler and Sligh, 1932). Therefore, slates which are to be used for roofing in towns where the air is defiled with SO_2 fumes from chemical industries or from the combustion of coal in furnaces and stoves, should first be analysed for $CaCO_3$.

Scaling of granite of monuments has the same cause. The Ca^{++} ions result from the mortar or from the decay of calcareous minerals which are originally present in the granite and the SO_4^{--} ions from the atmosphere (see Kessler et al., 1940).

Efflorescenses – mainly consisting of $CaCO_3$ – also cause mechanical desintegration by chemical action as the crystals which develop in the pores of the rock exert a wedging action.

Finally, galvanic corrosion of rocks may be very destructive under certain conditions. Thus a network of small short-circuited electric currents caused by differences in the amount of diffused oxygen from the air into several successive water layers (differential aeration current) may be present on the surface of rocks particles. At the anode, i.e. the part with the smallest amount of oxygen, the rock material is dissolved and at the cathode oxygen is reduced to OH^- ($2H_2O + O_2 + 4\ e^- \rightarrow 4\ OH^-$). Or, if the current is very intensive, hydrogen gas is formed at the cathode ($2H^+ + 2\ e^- \rightarrow H_2$). An excess of OH^- may lead to precipitation of insoluble $Ca\ (OH)_2$, $Mg(OH)_2$, or sesqui- and manganous hydroxides as a porous film on the anode. By films of insoluble precipitates or a film of hydrogen gas the resistance of the circuit is increased and consequently the destructive corrosion reaction is hindered. Flowing acidic waters rich in oxygen will thus be most destructive.

Galvanic corrosion is greatly increased by electrolytes as they decrease the resistance of the system considerably, because the electromotoric force of a circuit depends on the current and the resistance. Galvanic corrosion is furthermore increased by temperature as an increase of temperature leads to a decrease of the resistance. Thus, the specific conductance (χ) of water of 25 °C in contact with carbon dioxide of the atmosphere is about 1.4×10^{-1} ohm^{-1} cm^{-1}. However, brackish water has at 5 °C ca 5000×10^{-6} ohm^{-6} cm^{-1} and at 25 °C = ca 8000×10^{-6} ohm^{-1} cm^{-1}. Ocean water has ca 33000×10^{-6} ohm^{-1} cm^{-1} and 53000 ohm^{-1} cm^{-1}, respectively. As the electrolyte concentration increases, the corrosive rate goes through a maximum = ca 0.5 N solution (approximately equivalent to that present in ocean water) and then decreases. The decrease is caused by a decrease in oxygen solubility at the higher concentrations (see for details Thomas et al., 1934).

Corrosion rate goes also through a maximum when the temperature is increased as solubility decreases when temperature increases.

A high conductivity of the solution furthermore permits cathode and anode areas to be active at a farther distance from each other.

For every coulomb of galvanic current which flows a definite weight of anode (rock) material dissolves: Thus,

$$W = \frac{Mit}{z\ 96500}, \text{ in which}$$

W = weight of the dissolved anode material in grams;
M = atomic weight of the dissolved anode material;
i = galvanic current in Ampères;
t = time of flow of current in seconds;
z = valence of the cations formed at the anode.

Chemicals, which form insoluble protective films or which decrease the corrosion rate of the metal to be protected called inhibitors, e.g. phosphates, silicates, carbonates, and magnesium-, zinc-, nickel- salts respectively are applied to decrease galvanic corrosion. Another procedure to decrease galvanic corrosion is cathodic protection. In this case the negative side of a direct low voltage current (30 to 50 Volt) of high density (100–200 amp.) produced by a rectifier is connected with the material to be protected. From there the current travels to scrap steel anode pipes placed in the soil at some distance from the material. Cathodic protection is commonly used (see e.g. Uhlig, 1955) – to prevent galvanic corrosion of oil pipes and oil tanks in soils with a high salinity (desert soils with seasonal rains). It however cannot be applied to prevent corrosion of rocks and gravels because the latter have a too high specific resistance = ca 10^6 to 10^8 ohm cm^{-1} against ca 10^{-5} ohm cm^{-1} for iron.

DISCUSSION

From the above it may be concluded that the suitability of a rock or gravel for civil and rural engineering practices depends on many factors. Besides mechanical and economical factors (foundations, roof spans in mines, cost of transport), there are architectural and decorative considerations (pillars, colour of monuments) and the rock must moreover be resistant to weathering action. The value of a rock for road construction depends largely upon the extent to which it will resist the destructive influences of traffic. Moreover, when used in macadam roads, it depends on the cementing properties (kind of weathering products) of the rock. Thus, a rock which is unsuitable for one purpose may be the right material for another.

By a petrographic analysis, which is a quick inexpensive method *(microscope, polishing machine)* if used by an experienced investigator, the nature of a rock can be identified with great accuracy.

However it does not give information about mechanical strength and resistance to weathering agents of the rock in situ, which properties are in fact, the most important for the civil and rural engineer. He is less interested in the exact identification of a rock.

The mechanical method does not give information about the durability of a rock against weathering conditions. Moreover, mechanical analyses may be largely influenced by moisture condition and the direction in which the sample is analysed.

By chemical analysis valuable information can be obtained about the durability of the rock against weathering conditions. However, chemical analyses are not only laborious and expensive, but various instruments and much room are also needed.

The d.t.a. method is very quick and thereby the instrument is not complicated and needs small space only. Although this procedure is not quantitative (Van der Marel, 1955) – it gives preliminary valuable information about the nature of a rock and its state of weathering.

From the above it follows that each method has its own merits. Only by using them all, definite information can be obtained about the properties of the rock to be used in the prospective construction and about its future behaviour against the weathering agents in situ. Yet, unequal distribution of the stress on the surface of the rock particles, caused by bad filling of the joints with mortar, unequal settlement of the construction, swaying of tall buildings due to storms, fatigue effects of the rocks caused by strong torsion, flexure or tension and large differences in thermal expansion between the rock and its frame construction,¹) may upset all predictions based on analyses and theoretical calculations. Therefore, to avoid catastrophes in the future, an adequate security factor should always be taken in the calculations of rock constructions.

(Submitted 1959)

SAMENVATTING

Verschillende gesteentesoorten en hun verschillende eigenschappen worden besproken, speciaal met het oog op het gebruik ervan voor civiel- en cultuurtechnische werken.

Bij mechanisch gesteente-onderzoek zijn de resultaten zeer afhankelijk van het vochtgehalte en de richting waarin het gesteentemonster wordt onderzocht. De verkregen cijfers geven derhalve alleen informatie over de kwaliteit van het monster op een bepaald ogenblik tijdens de test, zodat men daaruit niets kan voorspellen met betrekking tot toekomstige gedragingen in situ. Deze hangen ook af van de verdeling van de op het gesteente werkende krachten over het gesteente-oppervlak en van de plaatselijk zeer wisselende omstandigheden ten aanzien van de verwering.

Verwering van gesteente is afhankelijk van de hoeveelheid vocht, zuurstof,

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¹) Thermal expansion coefficient of iron and steel = 10 to 11 × 10^{-6}, marble = 4 to 16 × 10^{-6}, granite = 6 to 9 × 10^{-6}, slate = 9 × 10^{-6}.

electrolyten en zuurgraad evenals van de grootte van het oppervlak en de snelheid waarmede verweringsprodukten worden afgevoerd en ten gevolge waarvan het verweringsproces kan voortgaan.

Vooral bij de waterlijn van zeewater met een hoog zout- en zuurstofgehalte werken sterk destructieve krachten. Bijzonderheden hiervan worden vermeld.

Eveneens worden voorbeelden gegeven van de toepassing van de differentiaal thermaal-, röntgen- en chemische analyse bij de waardering van gesteenten voor civiel- en cultuurtechnische doeleinden.

ZUSAMMENFASZUNG

Verschiedene Gesteinsarten und deren Eigenschaften in zivil- und kulturtechnischer Hinsicht werden einer Besprechung unterzogen. Mechanische Untersuchungen werden erheblich beeinfluszt durch Feuchtigkeitverhältnisse und die Richtung in welcher die Gesteinsprobe analysiert wird.

Ein mechanischer Test erteilt daher nur Auskünfte über die Qualität eines Gesteins während eines bestimmten Moments in der Testapparatur und es ist nicht möglich daraus auf das künftige Verhalten eines Gesteins zu schlieszen. Letzteres wird bedingt durch die Verteilung der Angriffspunkte der Kräfte über die Gesteinsoberfläche und auch durch die örtlichen Verwitterungsverhältnisse welche erhebliche Differenzen aufweisen können.

Die Gesteinsverwitterung wird bedingt durch den Gehalt an Wasser, Sauerstoff, Elektrolyte und den Säuregrad. Auch die exponierte Flächengrösze und die Geschwindigkeit des Abtransports der Verwitterungsprodukte nachdem ein Fortschreiten der Verwitterung wieder möglich ist, sind wichtige Bedingungen.

Besonders nahe der Wasserlinie des hoch-salzigem und auszerdem sauerstoffreichem Meerwassers sind die auf das Gestein einwirkende destruktiven Kräfte besonders stark. Einzelheiten davon werden erwähnt.

Auch Beispiele werden gegeben von der Anwendung der Differential thermal-, Röntgen- und chemische Analysen bei der Bewertung von Gesteinsarten für zivil- und kulturtechnische Zwecke.

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