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by Kalevi Kauranne

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ON THE ABRASION AND IMPACT STRENGTH OF GRAVEL AND ROCKS IN FINLAND

BY

KALEVI KAURANNE

WITH 23 FIGURES AND 33 TABLES IN TEXT AND TWO PLATES

GEOLOGINEN TUTKIMUSLAITOS
OTANIEMI 1970

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PREFACE

The present study is based on the laboratory investigation of aggregates used for road surfacing during the years 1961—1968 in Finland. The material consists of macadam, taken from bedrock by blasting, and gravel, taken from stony gravel deposits. All the material was granulated in field crushing plants.

The laboratory work was done in the Central Laboratory of the National Board of Public Roads and Waterways of Finland by numerous laboratory assistants, who all deserve special thanks for their excellent work. The statistical treatment was done by Miss K. Tainio, Ph. M., and Mr. J. Kokkila, Civ. E. . The thin sections of the rocks were made by Mr. N. Massinen and they were studied microscopically by Mr. J. Pekkarinen, Ph. M. . The drawings were done by Mrs. R. Tapanainen and the photos taken by Mr. E. Halme. The author's original English manuscript was corrected by Mr. P. Sjöblom, M. A. . I want to express my warmest thanks to them all for their good assistance.

Professors J. Donner, A. Mikkola and V. Okko have kindly read the manuscript and given valuable advice regarding the treatment and presentation of the results. Professor U. Soveri, my former chief and former head of the Soil Investigation Bureau of the National Board of Public Roads and Waterways, followed the investigation with keen interest and on innumerable occasions discussed the problems of aggregate strength and its geographical distribution. He also made the arrangements necessary to perform the special tests of aggregates in the Road Laboratory of the Institute of Technical Research. I appreciate, moreover, the various opportunities offered me to discuss these problems with my Scandinavian colleagues, notably Mr. A. Grønhaug, M.S. (Norway), and Mr. P. Höbeda, M.S. (Sweden), while participating in the work of the Stone Material Committee of the Interscandinavian Road Union. I am deeply grateful to all those mentioned for their most valuable help.

I also wish to express my gratitude to Professor Herman Stigzelius, Director of the Geological Survey of Finland, for accepting my manuscript for publication in the series Bulletin de la Commission Géologique de Finlande.

I wish to acknowledge the grant given me by the National Board of Public Roads and Waterways of Finland and the permission to use the material collected. And I am indebted to the Institute of Technology for letting me use its data computers as well as to the Foundation for the Investigation of Natural Resources in Finland for the material assistance which enabled me to carry out the study.

Tampere, April 1970 *Kalevi Kauranne*

Kauranne, Kalevi 1970: Abrasion and impact strength of gravel and rocks in Finland. *Bull. Comm. géol. Finlande N:o 243.* 64 pages, 23 figures, 33 tables and two plates.

This study deals with the abrasion resistance and impact strength of gravel and bedrock used as aggregates in road surfacing in Finland. The material consists of 1 747 samples of crushed gravel and 916 samples of macadam. The strength is determined by Los Angles abrasion and Swedish impact tests.

The mineralogical and textural factors affecting the abrasion and impact resistance of rocks are analyzed. The petrological, tectonical and other geological circumstances attending the geographical distribution of the strength of stones are reviewed.

According to the statistical analysis of aggregate investigation results, rocks with a high feldspar content, large grain size and high degree of porosity, isometric rounded grains and a low specific gravity are weak. Rocks with a high mica content, high specific gravity, small grain size and elongated angular grains are tough.

The toughest gravel is found in areas of basic, heavy bedrock and the weakest gravel in areas of acid, light bedrock. Also in areas of heavily faulted bedrock, the gravel is weaker than average. The strength anomalies are generally elongated, running northwest-southeast in line with the Pleistocene transport of glacial debris.

CONTENTS

INTRODUCTION

After World War II, the Soil Research Bureau of the National Board of Public Roads and Waterways undertook a large-scale investigation of road surfaces and their constituents, which gradually gained momentum in about 1950. This work was raised to the level of routine control of all the materials and products in 1960, when the Central Laboratory was built.

At the very beginning of the aggregate testing, it was observed that there were great differences in strength, owing to the mineralogical and textural properties of the material as well as to the region where the material was taken from. The data for the present investigation of the various factors of rock strength was collected by the routine aggregate studies during the years 1961—1968 and it consists of 1 747 gravel and 916 rock samples, all granulated in field crushing plants.

According to the Finnish specifications for aggregate of the bituminous surfacings the strength must be determined by the following two methods (RIL 1968): the Los Angeles abrasion test (ASTM C 131—55) and the Swedish impact test (Höbeda 1966). In both a limited grain-size fraction of aggregate is tested. The result obtained and the accuracy of the test depends on many factors, mainly grain size and particle form of the aggregate (Kauranne 1970). Therefore in the present study only the results of the B grading (Ø 9.6 to 19 mm) of the Los Angeles test and the 8—11.3 mm fraction with a flakiness of 1.4 of the Swedish impact test have been accepted. Particle form has been determined as two axis relations: elongation (length: thickness = c:a) and flakiness (width : thickness = b:a).

The abrasion resistance and brittleness of aggregate determined by the aforementioned tests are not specific and independent measures of rock strength (Höbeda 1969), for they both measure partly the same properties, depend on the same factors of rock and also on many other factors described by the author (Kauranne 1970) in the first part of the aggregate investigation. Because of these methods of rock strength investigation are standardized and widely used it may be permitted to use them in comparing the Finnish aggregates and in examination the strength of petrologically different rocks and samples from different areas.

Geologically, Finland consists of Quaternary drift and underlying Precambrian bedrock. The crystalline formations of bedrock may be grouped in two main categories: the metamorphic rocks with preferred mineral orientation of the Svecofennian and Karelian belts and the igneous rocks without preferred mineral orientation, see

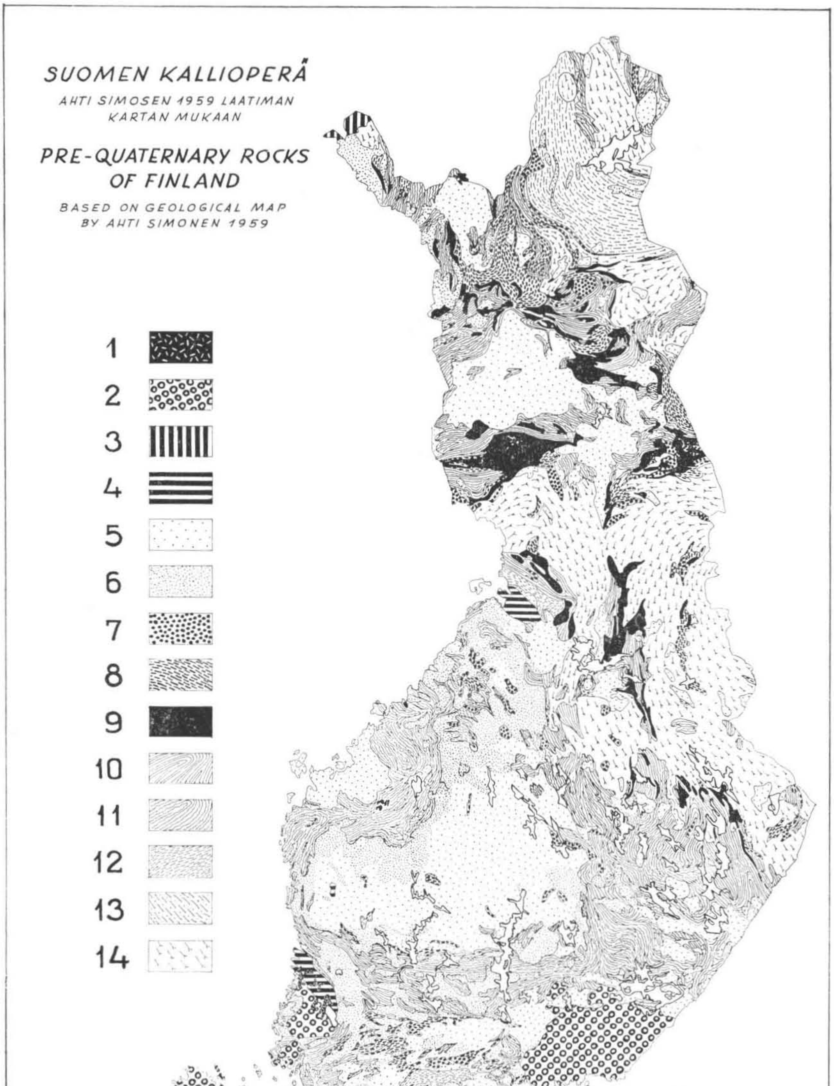


FIG. 1. Pre-Quaternary rocks of Finland, Simonen (1964) 1 = diabase, 2 = rapakivi, 3 = Paleozoic schists, 4 = siltstone and sandstone, 5 = granite, 6 = diorite, 7 = gabbro, 8 = amphibolite, 9 = quartzite, 10 = mica schist and phyllite, 11 = mica gneiss, 12 = quartz-feldspar schist, 13 = granulite, 14 = granite gneiss

Fig. 1 (Simonen 1960). The siltstones in the vicinity of the city Oulu and the sandstones in southwestern Finland are the largest formations of sedimentary rocks met with in our country.

The metamorphic complex of southern and western Finland is characterized by the predominance of mica schists and mica gneisses (together about 80 % of the total amount of the schists according to Simonen 1964) whereas the metamorphic complex of eastern and northern Finland is characterized by phyllites and mica schists (about 45 %), quartzites (26 %) and amphibolites (25 %). The large occurrences of granite gneiss in Karelia and granulite in Lapland may be mentioned separately. The schists of southern Finland are intensively folded, intersected by siliceous intrusions and partly migmatitized. The schists of eastern Finland are gently folded and tectonized.

The orogenic intrusives of southern, western and middle parts of Finland consist mainly of quartz-diorites and granodiorites (57 %) and granites (38 %) whereas in eastern and northern Finland the relation between granites and diorites is 73 % to 24 % (Simonen 1964). The largest anorogenic plutonites are met with in south Finland, the largest of them, rapakivi, occurring at the south-eastern border of the country as coarse ovoidal grained variety, called viborgite.

The crystalline bedrock has been the object of different stresses which have caused shear and fault lines cutting the bedrock into a mosaic-like pattern (Härme 1961). These tectonic lines are mainly orientated in southwest — northeast and northwest — southeast directions, see Fig. 2 (Mikkola and Niini 1968). The latter zones, especially have been exarated by the advancing Pleistocene glaciers to valleys cutting the relatively level bedrock surface.

The Quaternary minerogenic deposits consist mainly of glacial till, see Fig. 3 (Okko 1967) but also stratified drift, in ice marginal and redial deposits, is met with through the entire country, whereas the varved glacial and homogenous postglacial sediments occur only in areas formerly submerged by various stages of Baltic Sea, Donner (1965).

The radial eskers mainly trend towards northwest, whereas the ice marginal deposits run perpendicular to them. These deposits form the source of crushed gravel used as aggregate. The dimension of these formations, the degree of sorting and the grain size of the material differ greatly. The coarsest material is usually found in basal middle parts of the radial eskers and also on surface in ancient shoreline formations. According to Okko (1967) the glacial abrasion was strongest at elevated (hard, erosion resistant) portions of the bedrock. Therefore the composition of the material of glacial till and still more that of the eskers differs from the average petrological composition of the bedrock.

The material of the eskers was subject at least to two transports, first as glacial till carried by the ice, then as drift washed, ground, sorted and deposited by the meltwater streams. The soft and broken rocks were ground to fine debris whereas the hard and intact ones were enriched to the coarser fractions of the drift. The material of the eskers thus has been subject to double enriching of tough rocks.

The direction of both transports in average was towards southeast although local variations may have occurred. The source of the esker material should thus be situated northwest from the deposit. The distance of transport varied also according to local

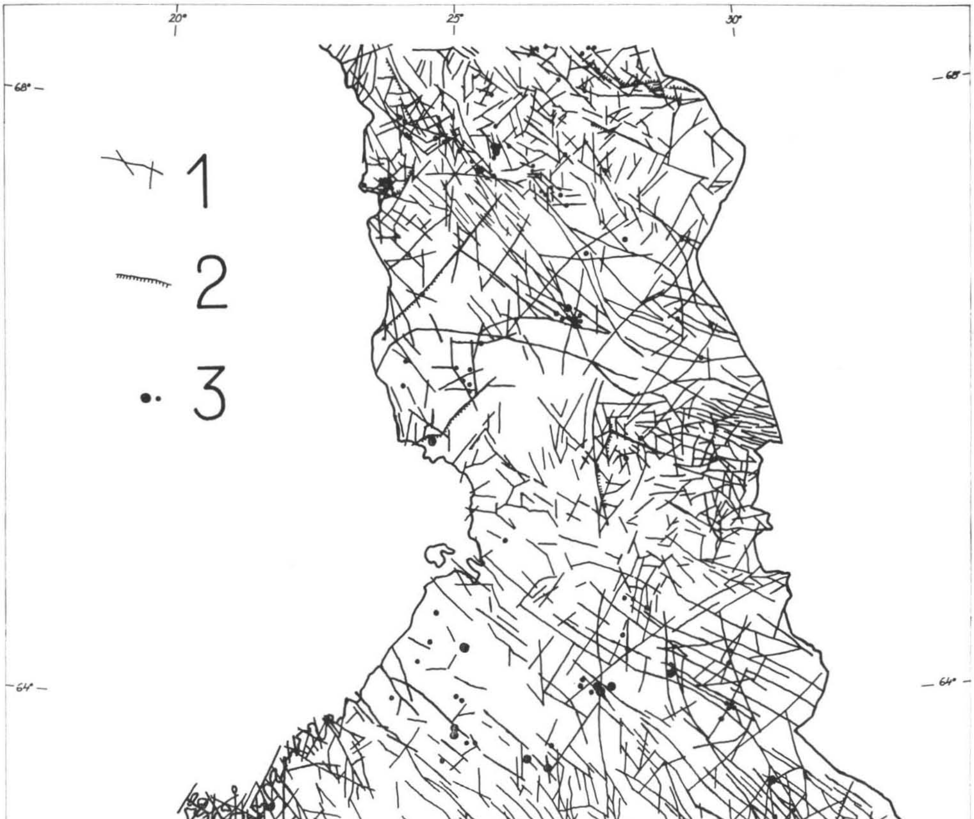


FIG. 2. Fracture lines of bedrock. 1 = fracture lines, 2 = probable vertical fault, 3 = ore deposit. From Mikkola and Niini (1968).

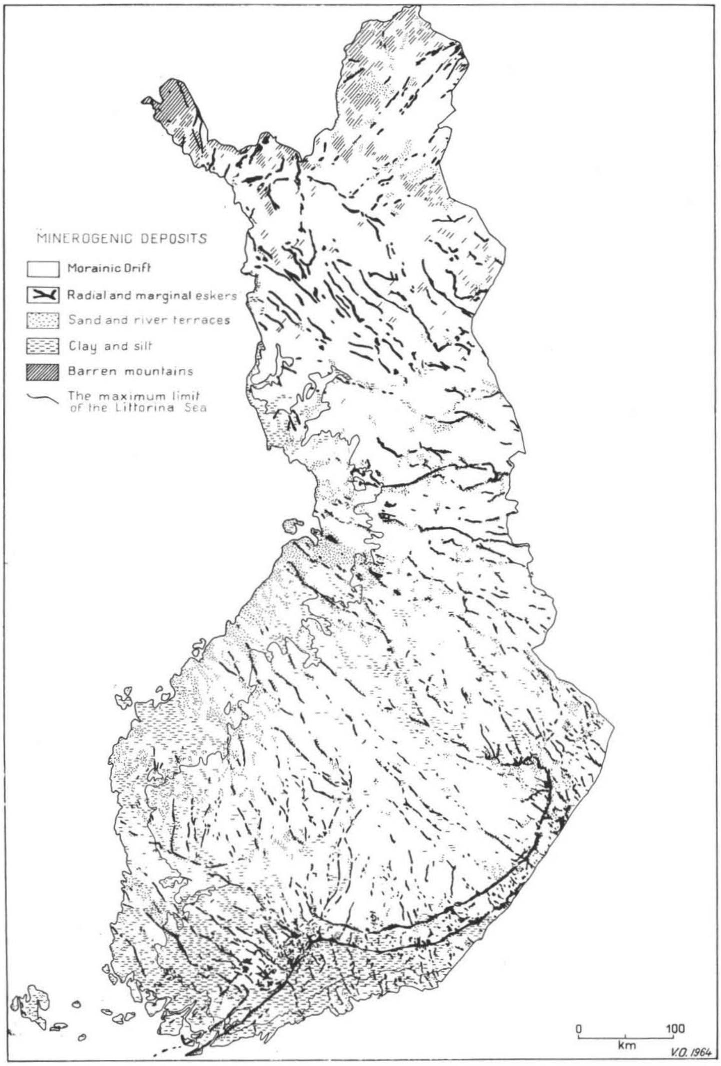


FIG. 3. The minerogenic Quaternary deposits of Finland, Okko (1960) 1 = glacial till, 2 = radial and marginal eskers, 3 = sand, 4 = clay and silt, 5 = barren mountains.

topography and other factors affecting the movement of glacial ice and the streams of meltwater. These problems have been studied by many workers, referred later (page 55) to, according to Virkkala (1958) the main part of glacial till has not been transported over 3 km and the material of eskers has been transported about 4 km farther (Hellaakoski 1930).

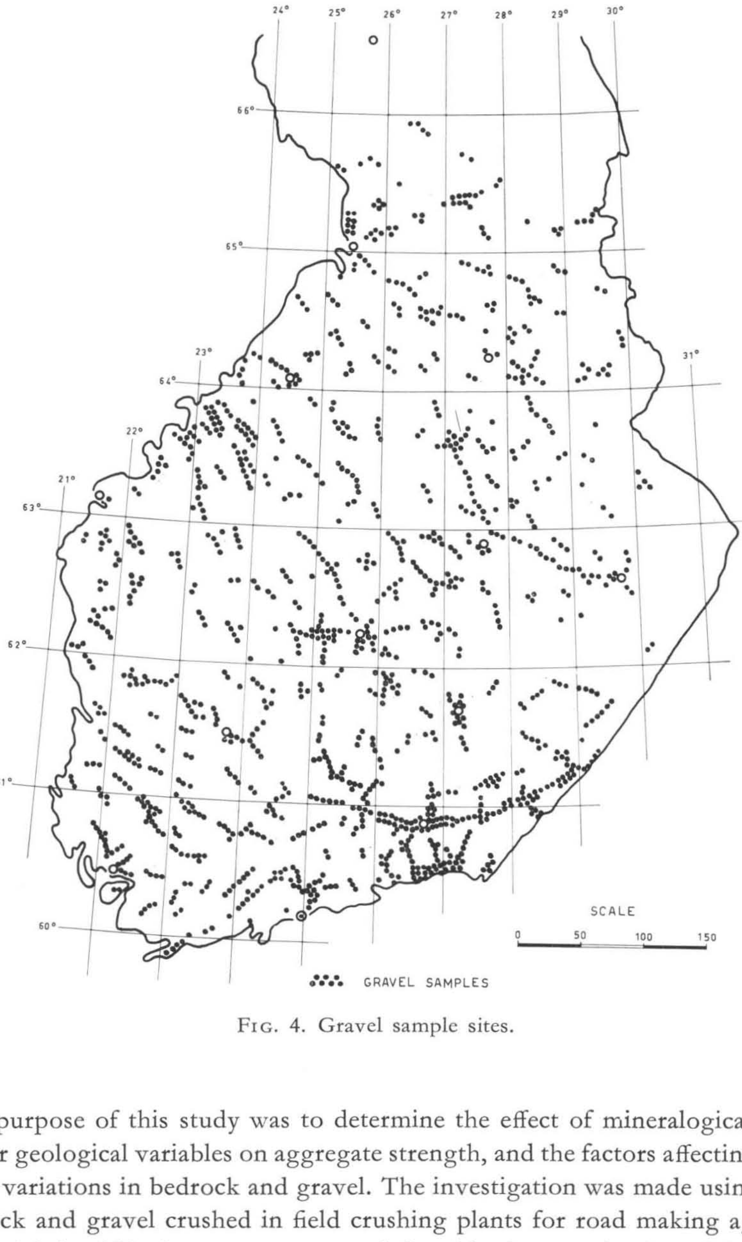


FIG. 4. Gravel sample sites.

The purpose of this study was to determine the effect of mineralogical, textural and other geological variables on aggregate strength, and the factors affecting regional strength variations in bedrock and gravel. The investigation was made using samples of bedrock and gravel crushed in field crushing plants for road making aggregates. The material should be homogenous enough for objective examination of the obtained relative strength values. The samples form a sparse net covering the entire Finland except for Lapland from where so few samples were obtained that it was left outside of a part of this study. The gravel sampling sites are shown in Fig. 4 and the sampling net reflects both the road network and the situation of the eskers.

The investigation methods consisted of the tests mentioned in the beginning and a microscopical study of 40 extremely tough or weak varieties of the commonest rock types. Because of the inaccuracy of the test methods used the results were treated statistically to achieve as reliable conclusions as possible.

PROPERTIES OF DIFFERENT ROCK TYPES

Samples of crushed gravel usually consist of very many rock types. Samples of macadam are petrologically more homogeneous. The following description of rock properties is based solely on the macadam samples studied. All the samples that showed some signs of weathering, the effects of blasting or other destructive phenomena were discarded. The material discussed consists of 482 samples. The different properties, given in tables, and their determination are described in the first part of this study (Kauranne 1970).

Igneous rocks without preferred mineral orientation

Pegmatite

Pegmatite is usually avoided when choosing material for road aggregate because it is known to be brittle; therefore there are only 9 samples in the study. The mean test results of pegmatite macadam from various districts of Finland is presented in Table 1.

TABLE 1

Mean properties of pegmatite macadam (9 samples) and their standard deviations

	arithmetic mean	standard deviation
specific gravity	2.63	0.03
Los Angeles value	34.8	4.59
Swedish impact value	69.0	8.48
flakiness	1.44	0.18
elongation	2.48	0.28
grain-size index (mm)	4.67 (14.0)	0.50
quartz %	39.9	—
feldspar %	54.8	—
mica %	5.3	—

Rapakivi

Rapakivi is a coarse or large-grained rock type, too. There are two areas in Finland where the bedrock consists solely of rapakivi, the southeastern and southwestern parts of the country, where this weak material must be accepted as aggregate for surfacing.

The distribution of strength properties is presented in Fig. 5 and the linear regressions in Fig. 6 (p. 20 and p. 21).

TABLE 2

Mean properties of rapakivi macadam (74 samples)

	arithmetic mean	standard deviation
specific gravity	2.67	0.04
Los Angeles value	29.9	3.40
Swedish impact value	60.5	7.39
flakiness	1.38	0.12
elongation	2.54	0.24
grain-size index (mm)	4.30 (10.0)	1.04
quartz %	37.2	4.54
feldspar %	53.3	2.30
mica %	9.5	6.86

Granites

According to Simonen (1964), the amount of granites among other intrusives in the bedrock of southern, western and middle parts of Finland is 37.6 %, while in the eastern and northern parts (including Lapland) the amount is 73.1 %.

The mean Los Angeles value for the granites of U.S.A. is 38 and for Hungary 33 (Temme 1965).

Some of the gray granites show a faint orientation of the mica, but this seems to have no effects on the shape of the particles in the macadam. The distribution of the strength properties is presented in Fig. 5 and the linear regressions in Fig. 6. The mean strength values of red and gray granites are almost the same only the standard deviations are greater in the latter group. The results show that the color of feldspar is no sign of different textural properties.

TABLE 3

Mean properties of red granite macadam (88 samples)

	arithmetic mean	standard deviation
specific gravity	2.66	0.04
Los Angeles value	24.9	4.19
Swedish impact value	55.9	9.72
flakiness	1.44	0.12
elongation	2.60	0.38
grain-size index (mm)	3.26 (1.7)	0.62
quartz %	36.5	4.70
feldspar %	52.7	4.14
mica %	10.1	7.93

TABLE 4

Mean properties of gray granite macadam (72 samples)

	arithmetic mean	standard deviation
specific gravity	2.69	0.04
Los Angeles value	25.9	5.97
Swedish impact value	52.6	11.76
flakiness	1.39	0.09
elongation	2.47	0.31
grain-size index (mm)	3.45 (2.0)	0.54
quartz %	38.2	3.64
feldspar %	53.3	2.41
mica %	8.1	5.20

Diorite

This group contains all the varieties of diorite. These rocks occur as comparatively large massifs in central Finland, but are found in other parts of the country, too. The proportion of granodiorites and quartz-diorites among other intrusive rocks in the southern, western and middle parts of Finland is 56.5 %, according to Simonen (1964) while in the eastern and northern parts it is 23.6 %.

Some of the diorite massifs near Jyväskylä have a 0.5 m thick, weathered mantle on the surface. Samples containing such weathered material have been discarded from the calculations.

TABLE 5

Mean properties of diorite macadam (39 samples)

	arithmetic mean	standard deviation
specific gravity	2.75	0.07
Los Angeles value	23.8	5.86
Swedish impact value	47.2	10.87
flakiness	1.39	0.08
elongation	2.68	0.52
grain-size index (mm)	3.19 (1.5)	0.47
quartz %	29.5	7.81
feldspar %	56.8	4.05
mica %	10.9	11.1

Gabbro

This group consists of all the gabbroic igneous rock types being studied in the laboratory from various parts of Finland. The proportion of such basic rocks, according to Simonen, is in the southern, western and middle parts of Finland 5.9 % and in the eastern and northern parts 3.3 %.

Basic massives in Finland are usually very small in size and therefore the variation in properties is apt to be great. The distribution of the strength properties is presented in Fig. 5. According to Temme (1965), the mean Los Angeles value for gabbros of the U.S.A. is 18.

TABLE 6

Mean properties of gabbro macadam (25 samples)

	arithmetic mean	standard deviation
specific gravity	2.88	0.07
Los Angeles value	23.8	3.35
Swedish impact value	49.5	9.72
flakiness	1.43	0.12
elongation	2.76	0.48
grain-size index (mm)	3.11 (1.4)	0.32
feldspar %	50.4	20.52
mica %	4.9	2.84
amphibole and pyroxene %	28.8	2.44

Diabase

Diabase occurrences in Finland are dykelike and rather narrow (Kahma 1951, Laitakari 1969). They are seldom met with in road cuttings and therefore the number of samples studied is small. When such a material is met with, it may have been reserved for surfacing and the lower courses of the road made of weaker material. Many of the diabase samples were so fine-grained that is was impossible to determine the mineral composition visually. Owing to the small number of samples studied, the mineral composition is not presented. According to Temme (1965), the mean Los Angeles value of diabases in the U.S.A. and Hungary is 18.

TABLE 7

Mean properties of diabase macadam (9 samples)

	arithmetic mean	standard deviation
specific gravity	2.81	0.06
Los Angeles value	19.3	7.61
Swedish impact value	46.2	7.99
flakiness	1.52	0.13
elongation	3.14	0.40
grain-size index (mm)	2.50 (0.25)	0.55

Metamorphic rocks with preferred mineral orientation

Granite gneiss

The group of granite gneisses consists of distinctly oriented granites and gneisses of a granitic composition, with a mica content under 15 %. These rocks occur all around Finland but are dominating in waste areas along the eastern boundary of the country.

Temme (1965) gives as the mean Los Angeles value for gneiss of the U.S.A. 45 and for Hungary 29.

TABLE 8

Mean properties of granite gneiss macadam (49 samples)

	arithmetic mean	standard deviation
specific gravity	2.70	0.05
Los Angeles value	25.4	4.88
Swedish impact value	56.4	7.85
flakiness	1.41	0.08
elongation	2.43	0.29
grain-size index (mm)	3.36 (1.8)	0.49
quartz %	35.6	5.28
feldspar %	49.3	4.38
mica %	12.8	6.64

Mica gneiss

In the group of mica gneiss are collected all the medium- or coarse-grained, distinctly oriented granite, granodiorite or diorite-like rocks containing over 15 % of mica.

These rocks are met with all around Finland, but they are concentrated in the so-called Svecofennian and Karelian schist belts. These zones are seen in the map of bedrock, Fig. 1.

TABLE 9

Mean properties of mica gneiss macadam (73 samples)

	arithmetic mean	standard deviation
specific gravity	2.75	0.07
Los Angeles value	24.0	7.07
Swedish impact value	50.3	11.62
flakiness	1.39	0.09
elongation	2.51	0.32
grain-size index (mm)	2.92 (0.8)	0.56
quartz %	35.0	2.94
feldspar %	45.2	3.12
mica %	19.4	5.95

Mica schist

The group of mica schist consists of medium- and fine-grained, mica-rich schists, with a mica content usually over 20 %. Mostly the mica is biotite; there are only a few samples of muscovite schists in the material. Mica schists occur mainly in Svecofennian and Karelian schist areas.

Some of the samples were so fine-grained that determining the mineral composition proved difficult; hence the values given above may not be very reliable.

TABLE 10

Mean properties of mica schist macadam (12 samples)

	arithmetic mean	standard deviation
specific gravity	2.76	0.05
Los Angeles value	20.5	7.02
Swedish impact value	52.8	12.30
flakiness	1.52	0.14
elongation	2.72	0.20
grain-size index (mm)	2.22 (0.1)	0.83
quartz %	32.1	2.57
feldspar %	33.8	3.84
mica %	34.1	5.98

Phyllite

Mica-rich, dense slaty rocks comprise the group of phyllite, but the graphite-bearing black schists are omitted. Phyllites are met with mainly in the aforementioned schist belts. The graphite-bearing varieties are concentrated in the North-Karelia (Pohjois-Karjala) and Vaasa districts. Black schists are very weak and therefore, if possible, avoided when road-building aggregates are selected.

The mineral composition is impossible to determine macroscopically.

TABLE 11

Mean properties of phyllite macadam (9 samples)

	arithmetic mean	standard deviation
specific gravity	2.75	0.03
Los Angeles value	15.5	3.70
Swedish impact value	36.9	4.10
flakiness	1.50	0.18
elongation	2.58	0.20
grain-size index (mm)	1.33 (0.03)	0.82

Amphibolite

Rocks varying in origin but rich in amphiboles (mainly hornblende) and distinctly oriented make up the group of amphibolite. They occur mainly in the aforementioned schist belts but are also met with outside them. According to Simonen, the proportion of amphibolites in the group of schists is 13.0 % in the southern, western and middle parts of Finland and 25.3 % in the eastern and northern parts of the country.

The grain size of many amphibolites is so small that no reliable determinations of their mineralogical composition can be presented. According to Woolf (1953), the mean Los Angeles value of amphibolites in the U.S.A. is 35.

TABLE 12

Mean properties of amphibolite macadam (14 samples)

	arithmetic mean	standard deviation
specific gravity	2.88	0.10
Los Angeles value	15.8	3.77
Swedish impact value	48.4	10.07
flakiness	1.70	0.11
elongation	3.31	0.41
grain-size index (mm)	2.60 (0.3)	0.52

Crystalline limestone

Crystalline limestone has been mixed with tougher rocks to lighten the colour of aggregate and make the asphalt surface reflect light better.

The limestones investigated are mainly calcitic and come from various deposits in southern, southwestern and southeastern parts of Finland, where the limestone content is, according to Simonen, 0.3 %. The eastern and northern parts of the country also supply limestones, but these varieties contain dolomite.

Most of the limestones studied have been discarded for various reasons. Included in the study, these should represent the typical crystalline limestones of southern Finland. On the average, they should also give a reliable picture of the strength of crystalline limestone.

Much limestone is used in the bituminous surfacing technique in the form of fine rock powder, as filler. For this purpose, calcite, likewise dolomite, is quite well suited, owing to its basic reaction.

According to Temme (1965), the mean Los Angeles value for limestones of the U.S.A. is 26 and that for marble 47.

TABLE 13

Mean properties of crystalline calcitic limestone macadam (4 samples)

	arithmetic mean	standard deviation
specific gravity	2.73	0.04
Los Angeles value	40.7	2.73
Swedish impact value	73.6	8.47
flakiness	1.45	0.09
elongation	2.60	0.29
grain-size index (mm)	3.75 (3.6)	0.50

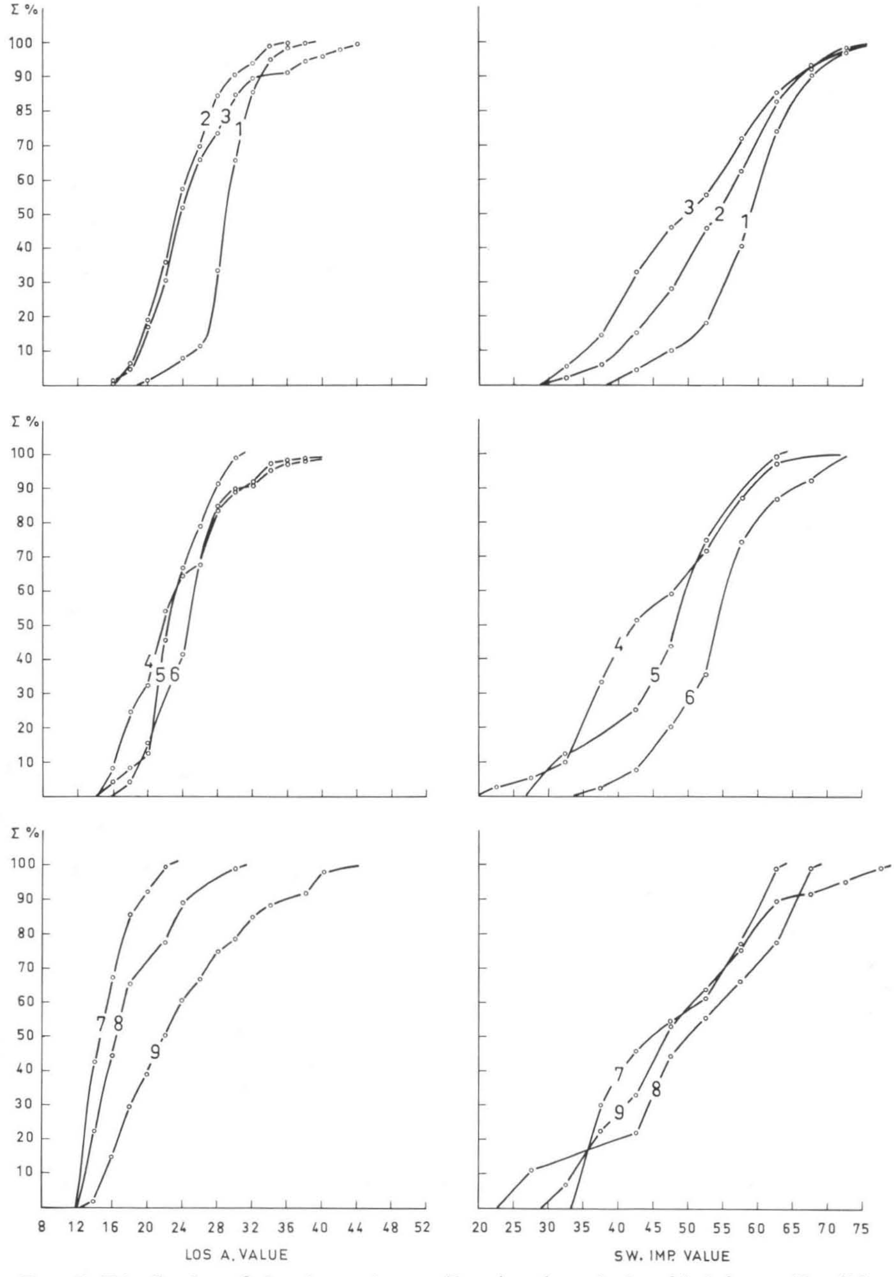
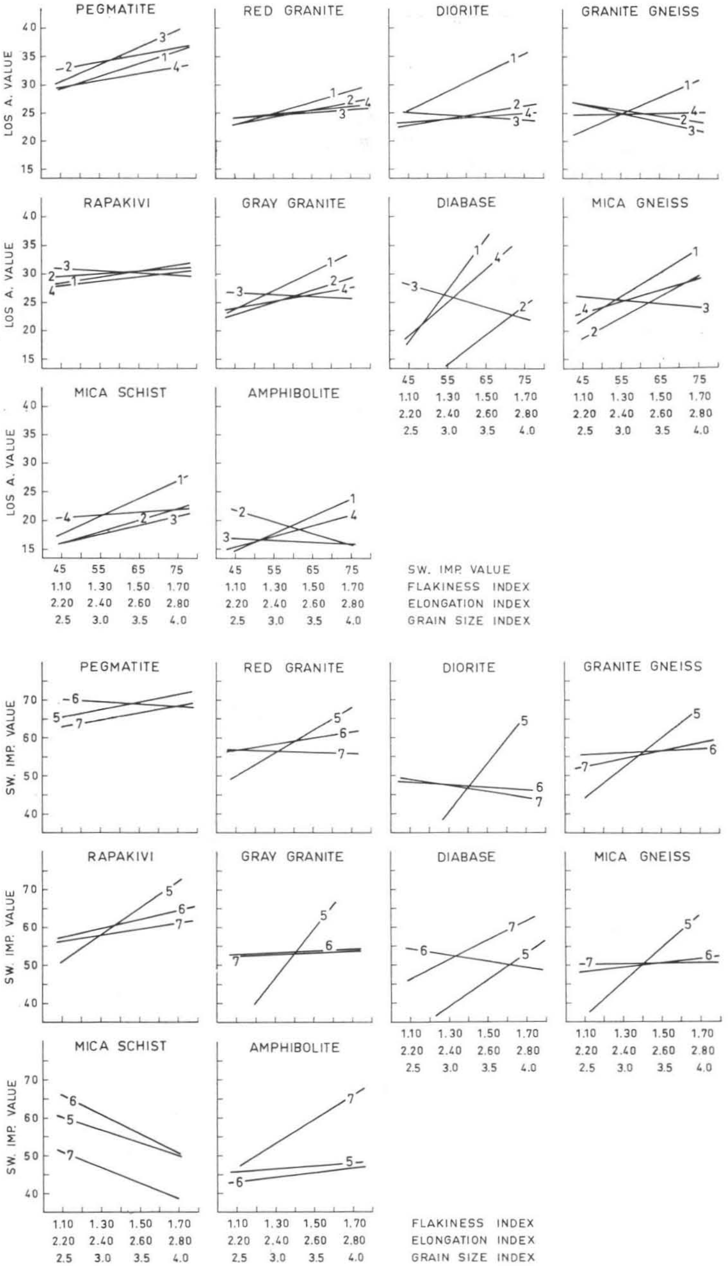


FIG. 5. Distribution of abrasion resistance (Los Angeles value) and brittleness (Swedish impact value) of macadam composed of different rocks, 1 = rapakivi, 2 = red granite, 3 = gray granite, 4 = diorite, 5 = gabbro, 6 = granite gneiss, 7 = amphibolite, 8 = mica schist, 9 = mica gneiss.



PEGMATITE, RED GRANITE, DIORITE, GRANITE GNEISS, RAPAKIVI, GRAY GRANITE, DIABASE, MICA GNEISS, MICA SCHIST, AMPHIBOLITE

FIG. 6. Regression of strength and other properties of macadam composed of different rocks, 1 = L.A./Sw.i.; 2 = L.A./flakiness; 3 = L.A./elongation; 4 = L.A./grain size; 5 = Sw.i./flakiness; 6 = Sw.i./elongation; 7 = Sw.i./grain size.

Comparison of rock types

When observing the standard deviations of the test results in the foregoing tables, one could see that as regards the specific gravity, which may be counted among the petrological properties, the deviations were very small and the greatest standard deviation was found in amphibolite (0.10), which is only 3.5 % of the mean specific gravity. The petrological macadam groups of tables 1 to 13 may therefore be assumed to represent real, petrologically homogeneous rock types. Comparatively, the mean test results may be designated for mean properties of the rock type in question.

Fig. 5 shows that the deviation of Los Angeles values in different rocks is smaller than that of Swedish impact values. Most homogeneous rock according to the variation of strength is rapakivi and most inhomogeneous mica gneiss. The dependence of strength values in different rocks on different aggregate properties is shown in Fig. 6.

To give a better basis for comparison, the mean test results are gathered in one and the same table (14) where also certain rock types appear that are present in the samples in such small amounts as to preclude separate mention.

The greatest variation in grain size occurred in rapakivi; the standard deviation of the grain size index 1.04 = 24 % of the mean. The greatest variation in abrasion resistance was exhibited by diabase, mica gneiss and mica schist, with about 40 % of the mean Los Angeles value; and the greatest variation in brittleness by mica schist, mica gneiss and gray granite, with nearly 25 % of the mean Swedish impact value. The greatest variations in particle form were exhibited by pegmatite and phyllite, with about a 12 % standard deviation of the mean flakiness index, as well as by diorite and gabbro, with a standard deviation of about 20 % of the mean elongation index.

TABLE 14

Mean properties of different rock types

	sp.Gr.	L.A.	Sw.i.	b:a	c:a	grain Ø mm
pegmatite	2.63	34.8	69.0	1.44	2.48	14.0
rapakivi	2.67	29.9	60.5	1.38	2.54	10.0
red granite	2.66	24.9	55.9	1.44	2.60	1.7
gray granite	2.69	25.9	52.9	1.39	2.47	2.0
diorite	2.75	23.8	47.2	1.39	2.68	1.5
gabbro	2.88	23.8	49.5	1.43	2.76	1.4
diabase	2.81	19.3	46.2	1.52	3.14	0.25
granite gneiss	2.70	25.4	56.4	1.41	2.43	1.8
mica gneiss	2.75	24.0	50.3	1.39	2.51	0.8
mica schist	2.76	20.5	52.8	1.52	2.72	0.1
phyllite	2.75	15.5	36.9	1.50	2.58	0.03
amphibolite	2.88	15.8	48.4	1.70	3.31	0.3
greenstone	2.86	13.1	46.4	1.49	2.96	0.03
leptite	2.65	15.5	46.2	1.59	3.00	0.05
quartzite	2.67	21.5	63.1	1.53	2.59	0.1
limestone	2.73	40.7	73.6	1.45	2.60	3.6

TABLE 15

The correlation on the properties of different rocks is presented in the right upper corner of the matrices and their regression coefficients in the lower left corner

1	a	b	c	d	e	f
a	1	0.33	0.24	0.91	—0.43	0.27
b	0.2	1	0.18	—0.04	0.25	0.14
c	5.9	8.2	1	0.67	—0.36	0.55
d	15	—1.2	0.4	1	—0.74	0.39
e	—6.6	70	—2.2	—6.9	1	—0.69
f	2.5	2.5	0.2	0.2	—0.04	1

2	a	b	c	d	e	f
a	1	0.27	0.07	—0.14	—0.15	0.11
b	0.1	1	0.55	0.37	0.24	—0.05
c	2.2	35	1	0.55	—0.44	—0.10
d	—2.0	11	0.3	1	0.42	—0.20
e	—13	47	1.3	2.6	1	—0.15
f	1.6	2.9	0.04	0.05	0.15	1

3	a	b	c	d	e	f
a	1	0.49	0.15	0.24	—0.07	0.23
b	0.2	1	0.41	0.38	—0.15	—0.03
c	6.9	34	1	0.63	—0.02	—0.02
d	2.7	9.7	0.2	1	—0.04	—0.09
e	—7.5	—36	—0.05	—0.4	1	0.18
f	1.5	—0.5	—0.004	—0.06	0.01	1

4	a	b	c	d	e	f
a	1	0.67	0.18	—0.06	0.05	0.21
b	0.3	1	0.52	0.12	0.15	0.07
c	12	66	1	0.21	0.02	0.19
d	—1.2	4.3	0.06	1	0.07	—0.41
e	6.4	40	0.03	0.5	1	—0.16
f	2.4	1.6	0.03	—0.2	—0.01	1

5	a	b	c	d	e	f
a	1	0.71	0.09	—0.19	—0.45	0.07
b	0.4	1	0.49	—0.10	—0.16	—0.14
c	6.7	67	1	0.31	0.02	—0.22
d	—2.1	—2.1	0.05	1	0.36	—0.32
e	—37	—25	0.02	2.6	1	—0.13
f	0.9	—2.7	—0.04	—0.4	—0.001	1

6	a	b	c	d	e	f
a	1	0.95	0.48	—0.56	—0.18	0.89
b	0.9	1	0.58	—0.47	0.10	0.74
c	27	35	1	0.15	0.79	—0.15
d	—11	—9.2	0.05	1	0.32	—0.79
e	—25	14	1.9	2.4	1	—0.73
f	12	11	—0.04	—0.6	—0.07	1

7	a	b	c	d	e	f
a	1	0.46	—0.10	—0.43	0.001	0.03
b	0.3	1	0.43	0.07	—0.16	0.02
c	—5.9	41	1	0.36	—0.26	—0.32
d	—7.2	1.9	0.1	1	—0.42	—0.03
e	0.09	—25	—0.4	—2.4	1	—0.13
f	0.3	4.4	0.001	—0.02	—0.02	1

8	a	b	c	d	e	f
a	1	0.70	0.24	—0.16	—0.25	0.26
b	0.4	1	0.36	0.15	—0.45	—0.09
c	18	46	1	0.15	0.04	0.07
d	—3.6	5.7	0.04	1	—0.12	0.48
e	—24	—70	0.05	—0.5	1	0.02
f	3.6	0.3	0.04	0.1	—0.2	1

9	a	b	c	d	e	f
a	1	0.49	0.20	0.23	—0.44	0.79
b	0.3	1	—0.19	—0.39	0.11	0.39
c	10	—17	1	0.37	—0.15	0.60
d	8.3	—2.4	0.3	1	—0.27	0.40
e	—67	29	—0.4	—1.1	1	—0.38
f	1.1	—8.5	0.13	0.05	0.001	1

10	a	b	c	d	e	f
a	1	0.80	—0.32	—0.09	—0.003	0.47
b	0.3	1	0.05	0.16	—0.06	0.66
c	—10	4.0	1	0.88	—0.08	0.38
d	—0.8	4.0	0.2	1	0.25	0.29
e	—0.1	—5.9	—0.1	1.0	1	—0.23
f	3.5	13	0.08	0.2	—0.04	1

a = abrasion resistance (Los Angeles value),
b = brittleness (Swedish impact value),
c = flakiness (relation width to thickness),
d = elongation (length/thickness),
e = specific gravity,
f = grain size index

1 = pegmatite, 2 = rapakivi, 3 = red granite, 4 = gray granite, 5 = diorite,
6 = diabase, 7 = granite gneiss, 8 = mica gneiss, 9 = mica schist, 10 = amphibolite

The smallest variations in specific gravity were registered for phyllite (1 %), in abrasion resistance for crystalline limestone (7 %), in brittleness for phyllite (11 %), in elongation for mica schist (7 %), in flakiness for granite gneiss (6 %) and in grain size for gabbro (10 %).

The most abrasion-resistant rocks proved to be greenstone, phyllite, leptite, amphibolite and diabase. The weakest rocks in this sense are crystalline limestone, pegmatite and rapakivi. The most brittle rocks are limestone, pegmatite, quartzite and rapakivi. The impact-resistant rocks are phyllite, leptite, diabase, greenstone and amphibolite. The heavy rock types seem to be tougher than the light ones. The order of toughness and that of weakness in both tests (Los Angeles test and Swedish impact test) are nearly the same, so the tests measure nearly the same properties, as indicated previously (Kauranne 1970) by their close correlation.

The best-shaped (most isometric) particles are obtained by granulation of the weakest rock types and the most elongated or broadest grains of the tough rocks. Also the degree of schistosity seems to play a role by forming flaked particles (compare the flakiness indices and the Los Angeles values of e.g., mica schist and phyllite). The correlation coefficients of different properties in different rock types are presented in Table 15.

The study of the relations between aggregate properties (Kauranne 1970) has shown that the greater the L. A. value the greater the Sw.i. value; the more flat or elongated the particles of the aggregate the greater the strength values (the weaker the material); the greater the specific gravity the smaller the strength values but the less isometric the particles of the aggregate; and the greater the grain size of rock the weaker is the aggregate, the more isometric its particles and the lower its specific gravity. According to these general rules the direction of the correlations should be

b	c	d	e	f	
+	+	+	—	+	a
	+	+	—	+	b
		+	+	—	c
			+	—	d
				—	e

(a = L.A.; b = Sw. i.; c = flakiness; d = elongation; e = sp. gr.; f = grain size index)

Pegmatite. The correlation between abrasion resistance and elongation is good; between flakiness and elongation, specific gravity and grain size, moderate; correlation coefficients of flakiness and grain size, elongation and specific gravity are high but in the »wrong» direction.

Rapakivi. There are only two pairs with a moderate correlation: brittleness and flakiness, flakiness and elongation.

Red granite. There exists a moderate or good correlation in the pairs, abrasion resistance — brittleness, brittleness-flakiness, flakiness-elongation; and a correlation was also noted between brittleness and elongation.

Gray granite. There exists a moderate or good correlation in the pairs, abrasion resistance — brittleness, brittleness-flakiness and elongation-grain size.

Diorite. There is good correlation between abrasion resistance-brittleness and a moderate one between abrasion resistance-specific gravity and brittleness-flakiness.

Diabase. A good correlation is found in the pairs; abrasion resistance-brittleness, abrasion resistance-grain size, brittleness-grain size, flakiness-specific gravity, elongation-grain size, and specific gravity-grain size. There are also high correlation coefficients but in the »wrong» direction in the pairs; abrasion resistance-elongation and brittleness-elongation; if these were so, the elongated particles would be tougher than the short ones. Diabase differs distinctly from the other rocks (see also Fig. 6).

Granite gneiss. There exists a moderate correlation in the pairs; abrasion resistance-brittleness, brittleness-flakiness. High correlation coefficients were found in the »wrong» direction between abrasion resistance-elongation and elongation-specific gravity.

Mica gneiss. There is a good correlation between brittleness-specific gravity as well as one with a »wrong» direction in the pair, elongation-grain size.

Mica schist. A good correlation exists in the pair, abrasion resistance-grain size, a moderate one in the pairs, abrasion resistance-brittleness and abrasion resistance-specific gravity.

Amphibolite. A good correlation was observed between abrasion resistance-brittleness and flakiness-elongation, and a moderate one between abrasion resistance-grain size and brittleness-grain size.

The best correlation exists between strength values and form values, but also grain size correlates well with nearly all the other properties.

But, as seen, the internal relations of properties determined in the laboratory depend much on the petrological properties. Brittleness of all rocks depends distinctly on flakiness but that of diabase and metamorphic rocks also on grain size and elongation. Abrasion resistance of diabase and metamorphic rocks depends also distinctly on flakiness of the particles of the aggregate. To give a better picture of the correlations existing between strength values and specific gravity and their dependence on rock type, the coefficients are presented separately in Table 16 where also the linear regression coefficients are given. The correlation of strength values in tough rocks is much better than that in weak rocks. The correlation of strength values and specific gravity is almost negative, just as it should be, and slighty better for the Los Angeles value and specific gravity than for the Swedish impact value and specific gravity.

The linear regression functions may be formed by using the given coefficients and the arithmetic means of properties presented in Table 14.

TABLE 16

The dependence of the correlation of strength values on petrological composition

Rock type	L. A./Sw.I.		L. A./sp.Gr.		Sw.I./sp.gr.		No. of samples
	r	*q*	*r*	*q*	*r*	*q*	
pegmatite	0.33	0.18	—0.43	—6.55	0.25	6.95	9
rapakivi	0.27	0.12	—0.15	0.22	0.37	3.49	74
red granite	0.49	0.21	—0.07	0.75	—0.15	— 3.58	88
gray granite	0.67	0.34	0.05	0.64	0.15	4.01	72
diorite	0.71	0.38	—0.45	—3.67	—0.16	— 2.48	39
gabbro	0.43	0.15	—0.45	—2.21	0.11	1.52	25
diabase	0.95	0.90	—0.18	—2.50	0.10	1.40	9
granite gneiss	0.46	0.29	0.001	0.01	—0.16	— 2.48	49
mica gneiss	0.70	0.43	—0.25	—2.39	—0.45	— 7.03	73
mica schist	0.49	0.28	—0.44	—6.65	0.11	2.90	12
phyllite	1.0	—	—0.60	—7.19	—1.0	—	9
amphibolite	0.80	0.30	—0.003	—0.01	—0.06	— 0.59	14
limestone	0.35	0.11	—0.99	—7.77	—0.55	—13.35	4

r = Pearson correlation coefficient; *q* = linear regression coefficient in the formula y = *q* (x—E) + B where E and B are the arithmetic means of the properties.

INNER FACTORS AFFECTING ROCK STRENGTH

The inner factors involving rock strength discussed here are mineralogical composition and texture including all the properties measured microscopically, as presented in the chapter relating to microscopical study (p. 32).

Mineralogical composition

The effect of mineralogical composition is presented in the form of correlation coefficients in Table 17.

TABLE 17

Correlation of mineral contents and specific gravity with the strength and form values of rock groups

	Stones		Crushed gravel		Rocks		Macadam	
	Q	F	Q	F	Q	F	Q	F
L.A.	0.21	0.08	0.16	0.22	0.08	0.23	0.04	0.20
Sw.i.	0.04	0.14	—0.05	0.18	0.11	0.13	—0.06	0.01
b:a	—0.16	—0.14	—0.06	—0.23	0.02	—0.24	—0.30	—0.24
c:a	—0.10	—0.19	0.003	—0.24	0.11	—0.22	—0.26	—0.24
	M	G	M	G	M	G	M	G
L.A.	—0.26	—0.32	—0.29	—0.35	—0.33	—0.32	—0.27	—0.22
Sw.i.	—0.02	—0.21	—0.15	—0.22	—0.18	—0.27	—0.12	—0.19
b:a	0.22	0.17	0.18	0.20	0.27	0.20	0.24	0.17
c:a	0.24	0.15	0.16	0.17	0.36	0.21	0.32	0.20

Q = quartz %, F = feldspars %, M = micas %, G = specific gravity.

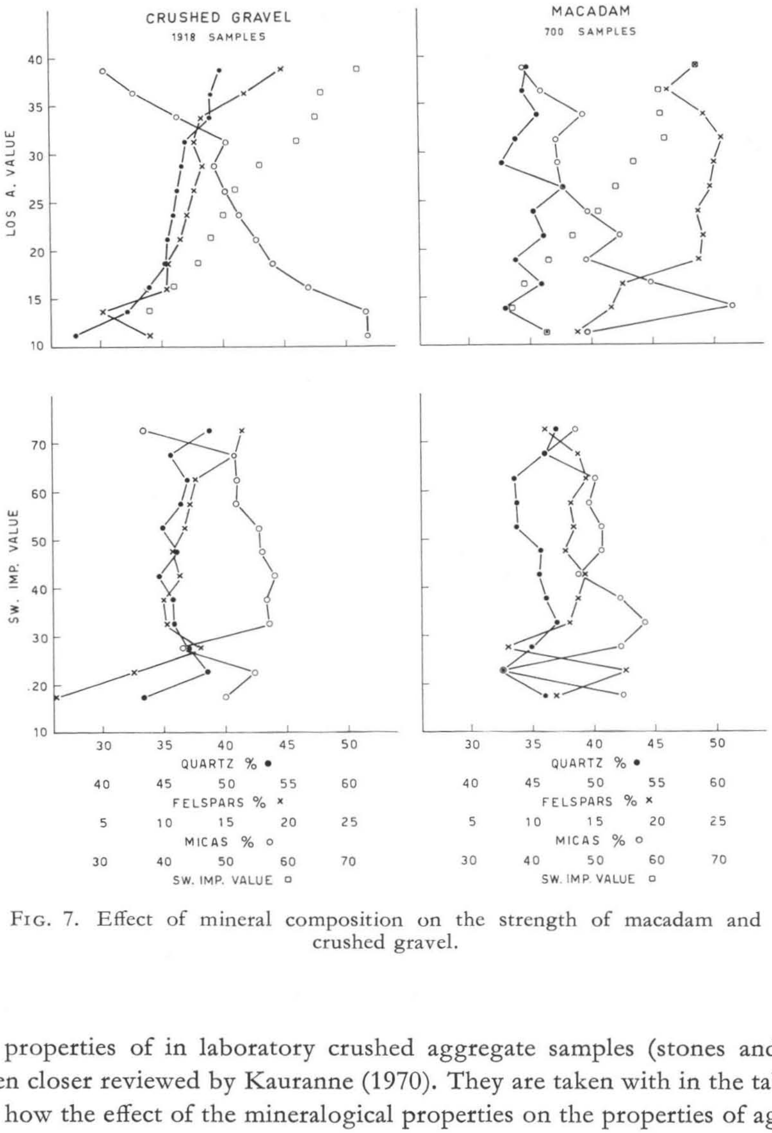


FIG. 7. Effect of mineral composition on the strength of macadam and crushed gravel.

The properties of in laboratory crushed aggregate samples (stones and rocks) have been closer reviewed by Kauranne (1970). They are taken with in the table only to show how the effect of the mineralogical properties on the properties of aggregate is greater in the product of a small laboratory jaw crusher than in the product of great field crushing plant granulators.

The effect of quartz, feldspars and mica on the strength of crushed gravel and macadam is perhaps better seen in the figure, in which the materials have been divided into separate abrasion resistance and brittleness classes and, further the mean content of the respective minerals in samples of every class is calculated and presented (Fig. 7).

The figure shows that tough rocks contain more mica than the weak ones do. In practice, it has been observed that surfacings made of mica-rich material do not stand up under the strain of climate (Zalesskii 1967, Soveri 1969) and traffic (Rengmark 1968, Höbeda 1969). As much as 14 % of the surface was damaged in less than 1 year on a road where mica-rich phyllite was used as aggregate (Hyyppä 1966). It is therefore remarkable that an increased mica content should improve the durability of stone in laboratory strength tests, especially in view of the fact that the higher mica content makes the stone particles at the same time flatter and more elongated. This can be understood only by the fact that mica in the investigated material mainly occurs as small flakes. It may be mentioned however that mica increases the drilling resistance of rock (Selmer-Olsen 1964). Weber (1966) has set limitations on the mica content in aggregates in a proposal for specifications as to stone material for different purposes.

The correlation coefficients of feldspar and strength values show that an increase in the content of feldspars makes material weaker; this effect is most clearly observed in abrasion resistance. The particle form becomes more isometric with increasing feldspar content.

Likewise remarkable is the fact that a higher guartz content, especially in material crushed in the laboratory seems to weaken aggregate. This runs contrary to the unpublished observations of Reihe (1967), who combined quartz and amphiboles to arrive at a tough mineral index. But in Finland the content of quartz dominates. From the stone materials of 25 road-building sites (about 100 samples) Reihe obtained the following relations, Table 18.

The toughest group of this material consists mainly of mica gneiss and diabase, the second group of granite and granite gneiss, and the weakest mostly of rapakivi.

The values in Table 17 also reveal that an increase in the quartz and feldspar content tends to reduce the amount of flaky and elongated particles, whereas an increasing mica content has the opposite effect.

Increasing specific gravity, amount of heavy minerals (micas, amphiboles and pyroxenes mainly) strengthens the stone material but weakens the particle form.

The effect of amphiboles and of calcite was studied separately, but owing to the inhomogeneity of the material and, correspondingly, of the results, together with the small number of samples, it is not tabulated here. It was observed that an increased content of amphiboles made the material more impact-resistant (*r* L.A/amph. % in rocks crushed in laboratory = —0.50, and in macadam —0.29, *r* Sw.imp/amph. %

TABLE 18

Means of technical properties, grouped according to the tough mineral index

Tough mineral index	5	4	3
Los Angeles value	22.4	23.9	26.7
Swedish impact value	54.8	54.6	54.6
flakiness	1.45	1.38	1.47
elongation	2.46	2.39	2.18
specific gravity	2.67	2.68	2.62

TABLE 19

Correlation of microscopically determined mineral relations and the strength and specific gravity of stone materials

	Q	F	M
Los Angeles value	0.27	—0.08	—0.15
Swedish impact value	0.28	0.05	—0.21
specific gravity	—0.37	—0.20	0.53

in rocks crushed in the laboratory = —0.44, in macadam 0.03, *r* b:a/ amph. % in rocks = 0.40, in macadam 0.33, etc.) but affected also the rise in form values. The comparative observations regarding calcite content showed the opposite effect (*r* L.A./calc. % in rocks = 0.70, in macadam 0.73, *r* Sw.Imp./ calc. % in rocks = 0.33, in macadam 0.61 and *r* b:a/calc. % in rocks = —0.33, in macadam 0.33, too). The effect of these minerals on elongation was not so clear as on flakiness.

For a closer investigation of the mineralogical properties of rock and their relation to the mechanical strength of the materials, 40 samples were taken so as to represent both exeptionally tough and exceptionally weak varieties of petrologically different rock types. In this series of microscopically studied samples, the correlations between mineral contents estimated from thin slides and the strength values of aggregate are shown in Table 19. The results obtained from the study of these extreme samples were not so good as desired. The correlation coefficients are rather low. These show only that quartz does not strengthen the rock and with an increase in the quartz content the specific gravity of rock becomes lower. The effect of feldspar in this series seems to be almost neglible. The increasing mica content would, according to the (small) correlation coefficients, strengthen the rock and also effect the rise in specific gravity. The linear regressions of technical properties and mineralogy of different types of aggregate are presented in figures 8 and 9. The factor analysis of these results is dealt with after the discussion of the effects of textural properties.

Texture

The following textural properties have been investigated: grain size, grain shape, smoothness of mineral surfaces, contact mass, degree of alteration (weathering), of fracturing and of orientation of mineral grains and the porosity of rock.

The correlation coefficients in Table 20 are again rather low, but somewhat greater than those of mineral amounts and technical properties (Table 17).

The effect of grain size on strength is greater in rocks and macadam groups than in partly rounded and smoothsurfaced gravelly material crushed in the laboratory or in the field. Increasing grain size weakens aggregate. Correlations with form values are better, and it is seen that increasing grain size produces more isometric particles in the aggregate. Now the effect is somewhat greater in gravelly materials. The linear regression functions for, e.g., macadam are: (see Fig. 9)

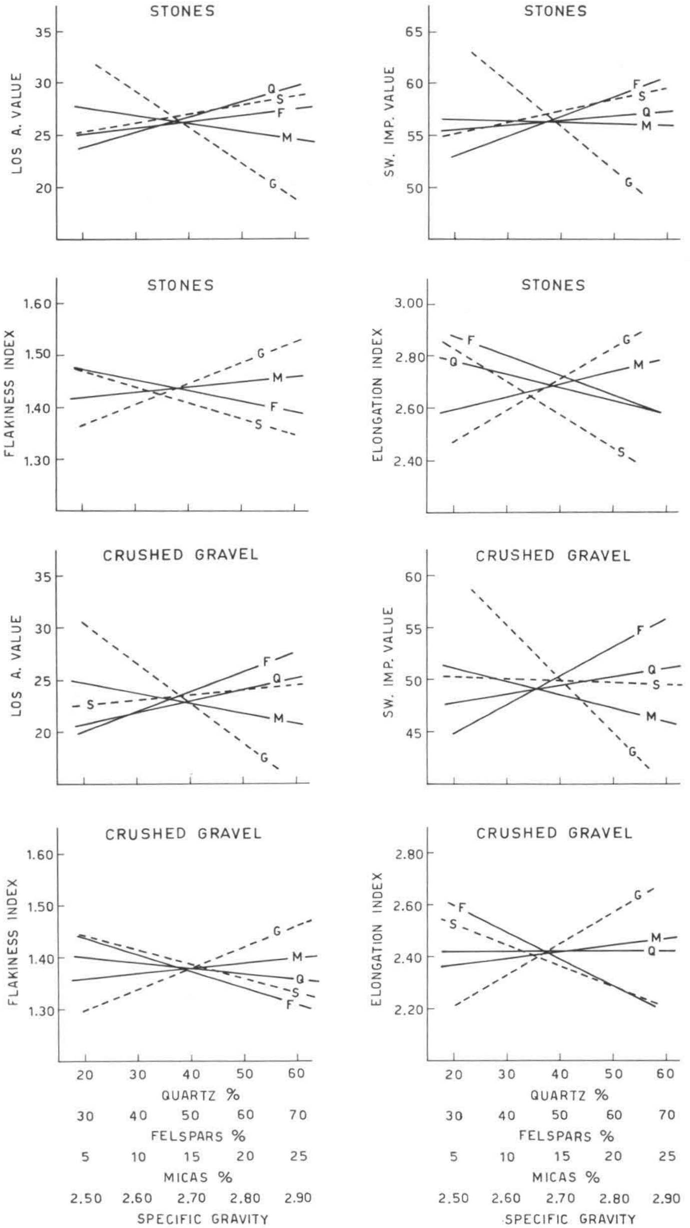


FIG. 8. Regression of strength, particle form and other properties in stones (crushed in laboratory)and gravel (crushed in field), Q = quartz; F = feldspar; M = mica; G = specific gravity; S = grain size.

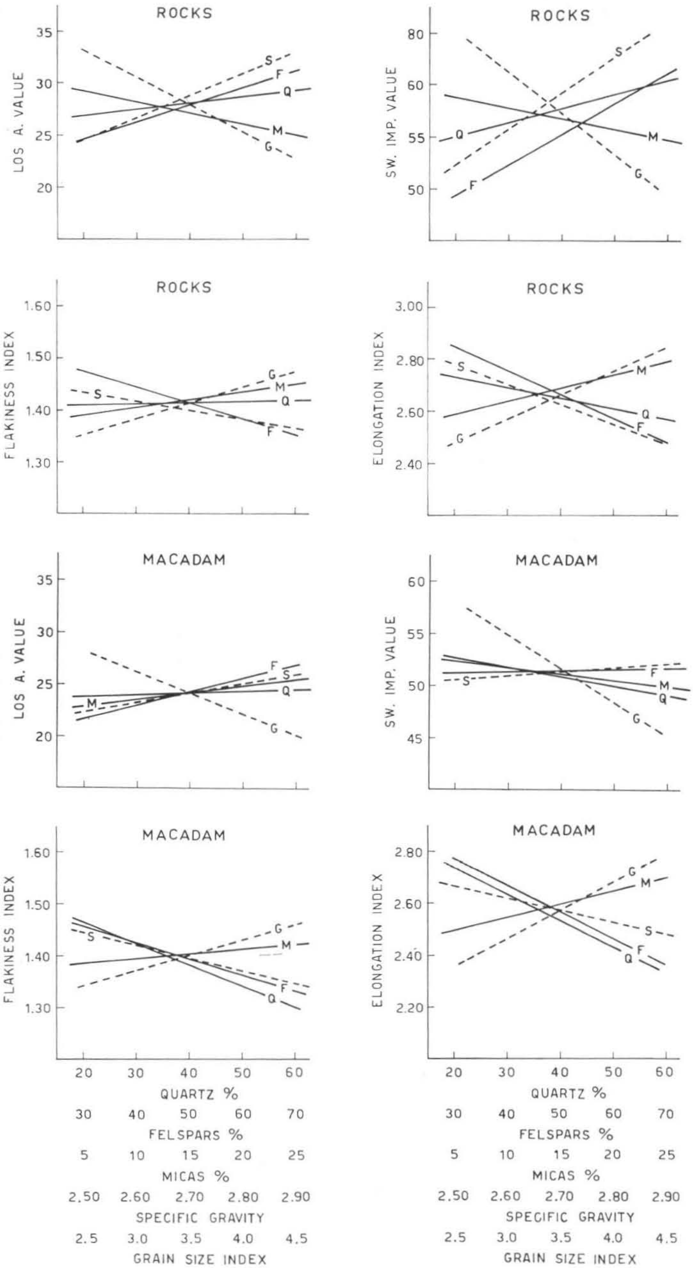


FIG. 9. Regression of strength, particle form and other properties in rocks (crushed in laboratory) and macadam (crushed in field).

TABLE 20

Correlation of grain size and the technical properties of rock material groups

	Stones	Crushed gravel	Rocks	Macadam
Los Angeles value	0.23	0.12	0.48	0.35
Swedish impact value	0.16	—0.05	0.44	0.15
flakiness	—0.39	—0.29	—0.28	—0.09
elongation	—0.43	—0.37	—0.32	—0.18

$$a = 2.7\ (f - 3.0) + 1.40 \qquad b = 2.3\ (f - 3.0) = 51.2$$
$$c = -0.01\ (f - 3.0) + 1.40 \qquad d = -0.09\ (f - 3.0) + 2.58$$

a = Los Angeles value, b = Swedish impact value, c = flakiness, d = elongation and f = grain size index.

The 40 samples of tough or weak varieties of different rocks were studied independently by Mr. J. Pekkarinen and the author to obtain the most objective possible results.

The microscopical observations were transformed into index figures as follows: mean grain size (under 0.1 mm, marked in the statistical treatment with the symbol 1; 0.1—0.5 mm, marked 2; 0.5—1 mm, 3; 1—2 mm, 4; 2—5 mm, 5; and over 5 mm, 6); grain shape (isometric rounded, 1; isometric angular, 2; elongated rounded, 3; elongated angular; 4; long rounded, length over 2.5 times thickness, 5; long angular, 6); grain surface (sutured mineral grain surfaces, 1; rough surfaces, 2; and smooth surfaces, 3); contact mass (no foreign mineral between actual mineral grains, 1; quartz seam between grains, 2; calcite, sericite, limonite seam between grains, 3); degree of alteration (all minerals fresh, 1; sericitization or other incipient alteration in minerals, 2; feldspars sericitized and mica limonitized, 3; most minerals weathered to unidentified mass, 4); degree of fracturing (no cracks in minerals, 1; quartz grains deformed, undulating extinction, 2; cracks in most mineral grains, 3; most grains fractured to small independent grains, 4); degree of orientation (random orientation, 1; faint orientation of elongated grains, 2; mica oriented, 3; distinct orientation of most minerals, 4).

The properties investigated are perhaps best revealed in the microscopical photos, plates 1 and 2, see the explanation of the plates. It was hoped by this investigation to shed light on the real reasons for the rock strength. It was noticed, however that this kind of investigation is rather subjective and it consists in itself sources of error. The correlation of textural properties and rock strength are given in Table 21.

All the correlation coefficients are small. Remarkable is the fact that all of them, except that of grain size, are negative, although the indices were arranged so that the growing figure was thought to reflect a weakening of structure. For instance: the greater the alteration or the longer the grains, the greater the index figure. The correlation coefficients tend to show that the increasing alteration of minerals would

TABLE 21

Correlation between textural properties and the strength of macadam made in the field crushing plant

	Pekkarinen		Kauranne	
	L. A.	Sw. i.	L. A.	Sw.i.
grain-size index	0.24	0.37	0.21	0.31
grain-shape index	—0.14	—0.26	—0.04	—0.01
grain-surface index	0.04	0.001	—0.19	—0.20
contact-mass index	—0.27	—0.07	0.06	0.01
alteration degree index	—0.25	—0.22	—0.24	—0.25
fracturing degree index	—0.17	0.06	—0.12	—0.16
orientation degree index	—	—	—0.22	—0.37

strengthen the rock. This result cannot be reliable, although one of the rock samples studied, diorite mylonitized to a nearly unidentified state (from Tervo, near Kuopio) was one of the toughest rocks in the series with a Los Angeles value of 15.8 and Swedish impact value of 32.4.

In the following discussion, only the observations of the author are used, because of the similarity of the correlations between strength and textural properties determined by both investigators.

As a basis for discussion, the mean and the standard deviation of the textural properties are given in Table 22.

The mean porosity is high compared, e.g., with Norwegian granites, 0.61—0.97 %, and gneisses, 0.40—0.75 % (Rosenqvist 1966), but small compared with Brazilian granites, 2.2—3.6 %, and gneisses, 1.1—3.7 % (Ruiz 1966) and Finnish granites 2.6 % (Aurola 1964).

The group was, as noted quite inhomogeneous, and the deviation of the values very great; and the results may not be reliable considered as a whole.

The correlation matrix of the material as whole, is presented in Table 23.

From the correlation matrix above, some interesting observations can be made, although within the limitations of this selected inhomogeneous material. There

TABLE 22

The arithmetic mean and standard deviation of the textural properties of the microscopically studied 40 extreme macadam samples

	mean	st. dev.
grain-size index	3.68	1.28
grain-shape index	2.55	1.13
grain-surface index	2.13	0.88
contact-mass index	1.79	1.19
alteration degree index	2.05	1.09
fracturing degree index	2.45	1.01
orientation degree index	1.73	0.99
Los Angeles value	29.2	14.6
Swedish impact value	58.8	18.4
porosity	1.52	1.82

TABLE 23

Correlation coefficients of microscopically determined rock properties and the technical properties of the macadam

b	c	d	e	f	g	h	i	j	k	l	m	n	o	
20	—20	03	13	16	—29	—06	44	—29	—36	—42	28	37	—20	a
1	—38	—05	—02	01	—001	—38	01	—01	29	28	—01	02	14	b
	1	11	02	—25	16	09	—09	29	12	—08	—25	—24	—31	c
		1	32	24	—02	05	—08	—07	—23	006	—004	—05	16	d
			1	59	19	—20	30	04	—20	—22	—26	—25	—18	e
				1	22	—12	10	—08	—18	—02	—10	—16	09	f
					1	—14	—37	73	48	39	—19	—34	03	g
						1	—55	03	—37	—40	—27	28	—09	h
							1	—53	—20	—36	—08	05	—33	i
								1	53	32	—15	—21	04	j
									1	73	—27	—40	—02	k
										1	—07	—22	53	l
											1	76	08	m
												1	—004	n

a = grain-size index, b = grain-shape index, c = grain-surface index, d = contact-mass index, e = alteration index, f = fracturing index, g = orientation index, h = quartz content, i = feldspar content, j = mica content, k = specific gravity, l = density, m = Los Angeles value, n = Swedish impact value, o = porosity % In the table only the decimals are given.

exists a distinct correlation coefficient $\gtrless 0.60$, between the degree of alteration and that of fracturing, between the degree of orientation and the content of mica, as well as naturally between the specific gravity and the density and between the abrasion and impact resistances.

There exists a moderate (*r* from 0.40 to 0.59) positive correlation between grain size and feldspars, micas and specific gravity, density and porosity, orientation and specific gravity and that and density, the two last-mentioned presumably because of the selected nature of the material.

A moderate negative correlation exists between grain size and density, quartz and feldspars, quartz and density, feldspars and micas and specific gravity and brittleness.

All the correlations mentioned are acceptable which shows that the material provides truely acceptable information and can be studied further.

The properties studied might be divided into the categories of texture (from a to g), mineralogy (from h to l) and mechanical properties (m and n), while porosity could stand apart, if not combined with specific gravity and density. The category of texture could de divided further into grain properties (a, b, c and g) and metamorphic properties (d, e and f).

The inner factors of rock strength were analyzed by the principal component and factor analyses using the common methods described in the textbooks of multivariate analysis.

The principal component analysis gave the results shown in Table 24.

The first component occurs in nearly all the properties determined. Its greatest power is in the specific gravity and in the positively correlated density, mica content and mineral orientation. It is not easy to determine the real content of the first component.

The second component has the greatest weight on alteration and the feldspar content positively correlating with it and the degree of fracturing. This component could be designated as that of metamorphic properties. Also the strength values have great weights, which apparently means that they depend very much on the metamorphic properties.

The third component has great power on grain shape and grain surface. This component could be designated as the component of grain properties.

The fourth component has weight on fracturing, contact mass and porosity. This component resembles the second component.

The best alternatives given by the factor analysis of this matrix are listed in Table 25.

The properties measured are not independent of each other; hence the interpretation of the factors must be taken with reservation. The analysis of the deviation of the residuals shows that these factors could not explain the correlation between quartz and feldspars.

Factor no. 1 seems to have nothing in common with the subfield metamorphic properties; it has a great (negative) weight on mica and orientation. The weight of the other factors on mica and orientation is close to zero. Therefore, the first factor might be designated mineral anti-orientation factor. It corresponds closely the first main component.

TABLE 24

Principal components of rock properties

Component	1	2	3	4	5	6
a grain-size index	—63	—20	23	—04	—42	14
b grain-shape index	13	—09	—71	—07	—19	03
c grain-surface index	24	—04	—68	—29	05	46
d contact mass index	—07	—22	—13	59	25	62
e alteration index	—06	—77	—17	37	—20	02
f fracturing index	—04	—58	—08	61	—16	—26
g orientation index	73	—11	—15	23	—47	—03
h quartz content	—26	56	—57	30	—02	—26
i feldspars content	—50	—60	—22	—44	02	13
j micas content	72	14	—25	11	—48	07
k specific gravity	81	02	23	—34	—17	08
l density	74	17	50	10	13	18
m abrasion resistance	—45	57	22	22	—36	23
n brittleness	—60	52	20	10	—34	20
o porosity	24	26	46	51	43	00

TABLE 25

Inner factors of rock strength

Factors	alternative 1				alternative 2			
	1	2	3	4	5	6	7	8
a grain size	61	0	0	0	—04	19	46	39
b grain shape	14	—17	—17	29	50	0	0	0
c grain surface	—45	07	12	—49	—43	—26	—002	—40
d cont. mass	03	44	23	22	—13	45	—09	09
e alteration	0	80	0	0	—24	65	23	—22
f fracturing	10	75	05	36	0	78	0	0
g orientation	—73	39	—03	20	10	17	—57	—53
h quartz	0	0	79	0	—56	02	—28	40
i feldspars	52	—01	—44	—37	0	0	82	0
j micas	—78	16	09	10	02	—07	—64	—47
k sp. gravity	—65	—26	—59	—02	53	—44	—34	—65
l density	—45	—17	—44	50	77	—10	—60	—31
m abrasion resist.	53	—34	43	44	08	07	—19	78
n brittleness	64	—40	41	29	0	0	0	82
o porosity	0	0	0	65	48	25	—49	20

No. 2 has nothing in common with the mineral contents or the grain properties except for the high weight on alteration and fracturing; it might be called the factor of metamorphism. This factors corresponds the second main component.

No. 3 has very small weights on the field of texture. The greatest weight is on quartz and specific gravity (although negative). This factor might be called the factor of light mineral content.

Factor no. 4 has the greatest weight on porosity; there is also weight on density and grain surface (negative), while the weights on mineral contents are negligible. This could perhaps be called the tightness factor.

These interpretations have been made with the help of other matrix axes variations, of which one, the next best alternative, is also presented in Table 25. It may be seen that factors 1 and 8, 2 and 6, 3 and 7 and 4 and 5 resemble each other closely.

The strength values are relatively best explained by the second main component (metamorphism) and by the factor of anti-orientation but many of the other main components and factors likewise has a relatively high weight on the strength values.

In the rotated factor matrices, the properties chosen as axes of the space of properties receive a very high weight in the direction of one axis and comparatively the weight zero in the direction of other axes. The high weights thus obtained somewhat disturb the interpretation. In the two alternatives presented in Table 25, separate properties are chosen as axes, but the two solutions are quite closely interconnected likewise the other solutions calculated but not presented here.

When the different rock types studied are inspected more closely, no general rules regarding the relations of mineral contents, texture, specific gravity or porosity with the strength values can be found. Therefore the results will be presented only in the light of certain examples (Table 26).

TABLE 26

Strength of four rapakivi samples compared with mineralogical and textural properties

Place	sp.gr.	L.A.	Sw.i.	a	b	c	d	e	f	g	n %	Q	F	M	A
Elimäki	2.64	20.0	44.2	4	2	3	4	3	2	1	1.1	30	55	10	5
Pyhtää	2.66	24.1	41.7	4	3	3	4	4	3	1	0	30	60	10	—
Valkeala	2.64	36.3	85.5	5	2	3	1	2	2	1	0.8	25	65	5	5
Kotka	2.62	39.4	77.4	5	1	3	4	2	2	1	1.1	30	65	5	—

a = grain-size index, b = grain-shape index, c = grain-surface index, d = contact-mass index, e = alteration index, f = fracturing index, g = orientation index, n = % porosity, Q = quartz content %, F = feldspar content %, M = mica content %, A = amphiboles content %.

When the strength test values rise and the rock becomes weaker, there is a tendency for the specific gravity, grain-shape index (grains become more isometric and rounded) and mica content to become lower and the grain size, porosity and feldspar content to become greater; but these phenomena are not distinct.

From the results, it was observed that, on the average, the porosity of heavy rock types was greater than that of light rocks — this may be true or partly due to some error in the specific gravity results caused by the air bubbles fastened on the rough particle surface. Now, also the specific gravity is lower and the content of feldspars higher in weak rocks, but other changes are not seen in properties with a diminishing strength (Table 27).

The samples for microscopical study, e.g. those presented in the foregoing two tables, were chosen according to petrology (mineral content, grain size and orientation); hence these properties might not show up in the comparisons. The strength-inducing factor of »light mineral content», however, is seen in the form of the effect of the feldspar content; also the factor of »tightness» is seen in the effect of specific gravity. The weakening effect of porosity on strength was seen clearly in the group of red granites and mica schists, the strengthening effect of specific gravity in the group of gabbros and quartzites, and the weakening effect of grain size in the group of gray granites, whereas the strength reducing effect of an increasing mica content was observed in the group of pegmatites. The effects of other properties were not clear.

The effect of fracturing which obviously should have been considerable, was not detected at all. Ramana (1969) has found that especially an increase in the relation of intersecting transgranular fractures with intergranular fractures weakens the rock. Gillot and Sereda (1966) report also the weakening effect on rock of residual internal stresses, which might be reflected in the undular extinction of quartz.

TABLE 27

Strength of four mica gneiss samples compared with mineralogical and textural properties

Place	sp.gr.	L.A.	Sw.i.	a	b	c	d	e	f	g	n %	Q	F	M	A
Rovaniemi	2.80	14.4	57.2	4	4	3	1	1	1	3	1.0	30	25	45	—
Noormarkku	2.75	16.7	42.5	5	2	3	1	2	4	2	0	25	40	20	15
Kemijärvi	2.80	36.7	63.0	3	2	3	1	2	2	3	0.4	20	40	40	—
Kuopio	2.69	47.0	68.0	5	2	3	3	2	3	3	0.7	30	50	15	5

GEOGRAPHICAL DISTRIBUTION OF ROCK STRENGTH

At the very beginning of the stone investigations, it was observed that there were some areas with tough stones and other areas with weak stones. For instance, the mica gneisses from Kuopio show anomalous low strength values: Los Angeles values from 28 to 47 and Swedish impact test values from 60 to 75, whereas the normal values for mica gneiss are around 20 and 50. Regional differences in the strength of stones have been reported also by Grønhaug (1964) and Woolf (1953). Höbeda (1969) has observed that the material of surficial parts of bedrock is weaker than deeper down.

The anomalous strength values would have necessitated a thorough study of the geology and tectonics of that area. It was not undertaken, but an effort was made to investigate the geographical distribution of stone material strength and make comparisons with petrological, tectonical and geophysical maps.

Two groups of material were used. The crushed gravel material, which derives from gravel deposits all around the country, is used altogether. It contains 1 747 samples (Fig. 4). Every gravel deposit represents on area far broader than the deposit itself. Thus every crushed gravel sample is like a mean mixture of the rocks occurring in the bedrock nortwest or towards the transport of glacial drift from the sampling site.

The other group, macadam, is rather inhomogeneous; the variation of strength values depends a good deal on the petrological composition of the sample material, which for some reason possibly might not be typical of the area. Because in this study only specific gravity and strength values are needed for the calculations, more samples could be accepted than previously for the mean calculations, or altogether 916 macadam samples.

These materials were first dealt with in the framework of the several districts from which the samples originate. A second grouping was then made according to a rectangular geographical grid, with co-ordinates as boundaries. The rectangular areas measure about 25 by 56 km. Owing to the small number of samples from the vast expanses of Lapland, this far northern region has been omitted from the second study and is not marked on the maps, either.

Gravel

Every sample of crushed gravel may be regarded as an average mixture of the components of the bedrock of its provenance. The gravel material has undergone many stages and stresses during its transportation; it has perhaps become altered from the character of the native bedrock; but because macadam samples are also affected by the technical treatment (e.g. blasting) to which they are subjected, crushed gravel may perhaps reflect the petrology of the area of its origin better than macadam does.

TABLE 28

Mean properties of crushed gravel material of different Road Building Districts

District	sp.Gr.	L.A.	Sw.i.	Quartz %	Feldspar %	No. of samples
Uusimaa	2.68	21.9	49.3	36	50	131
Turku	2.66	22.2	48.1	42	46	185
Häme	2.70	20.3	44.3	35	48	144
Kymi	2.65	26.2	52.1	38	52	233
Mikkeli	2.69	23.5	50.4	34	47	120
Kuopio	2.70	23.3	50.9	35	47	133
Keski-Suomi	2.68	23.3	50.0	36	50	189
Vaasa	2.68	23.7	48.5	36	46	146
Oulu	2.69	22.6	47.6	35	43	127
Lappi	2.69	27.8	58.5	41	44	71
Kainuu	2.68	24.9	53.1	38	46	118
Pohjois-Karjala	2.69	25.1	50.8	36	42	48
Keski-Pohjanmaa	2.70	18.6	44.7	34	45	99

The arithmetic means of the specific gravity, Los Angeles value and Swedish impact value of crushed gravel of different districts are presented in Table 28 and in Fig. 10.

Specific gravity does not vary much. The lowest values have been measured in the Kymi district of southeastern Finland and the highest in the Keski-Pohjanmaa (Central Bothnia) district on the western coast.

The weakest stones have been met with in Lappi (Finnish Lapland) and in the Kymi district. The toughest stone material originates from the Keski-Pohjanmaa and Häme districts.

These areas are too large to enable comparison with the petrological map of the bedrock, which is presented after Simonen (1960), as Fig. 1.

A better possibility for this is afforded by the maps in which the land is divided in the aforementioned rectangular areas. The material of this study is unevenly distributed; there are areal rectangles without samples and rectangles providing numerous samples; but still the picture of the total distribution is quite illuminating.

Figure 11 shows the distribution of the arithmetic means of the specific gravity of the crushed gravel deriving from the various rectangular areas. No great regional differences occur. But besides certain smaller areas of low specific gravity, there is a larger tract along the southeastern border of the country which falls in the rapakivi belt presented in the map of bedrock. There are also many large elongated, areas, running nearly north-south with a specific gravity of over 2.70; these do not closely resemble any features of the bedrock but fall partly on schist belts containing amphibolites and other heavy rock types. The specific gravity distribution map resembles in many of its features the Bouguer gravity anomaly map, Fig. 12, according to the measurements of the Geodetic Institute of Finland. Especially the area of light gravel overlying the rapakivi zone in southeastern Finland agrees with the negative gravity anomaly, compare Veltheim (1962), Puranen (1963) and Laurén (1970). Close to

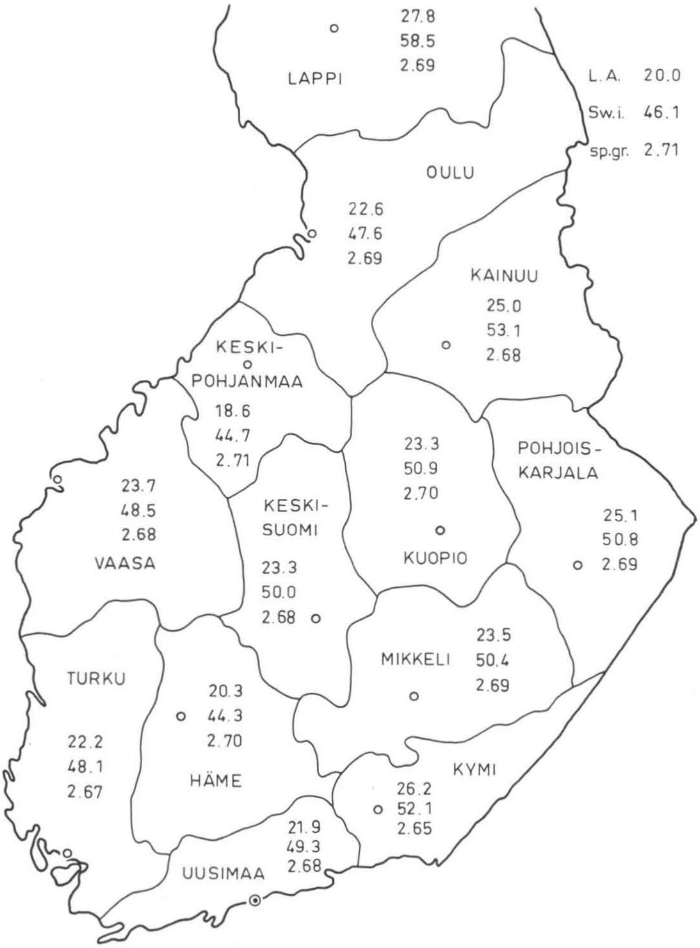


FIG. 10. Mean abrasion resistance, brittleness and specific gravity of gravels of different Road Building Districts.

Ylivieska and in the area west of Helsinki there also occurs a faint correlation of heavy gravel with the positive gravity anomaly.

Figure 13 presents the distribution of the mean Los Angeles values (abrasion resistance) of the crushed gravel material. It resembles the specific gravity map in the form of the anomalies. The area of weak stones in the vicinity of Kouvola falls in the rapakivi belt referred to. The large area of weak material on the eastern border of the country falls partly on the Karelian schist belt and on the gneiss area on its eastern side. The areas of tough stone material around Tampere and Ylivieska fall on the heavy areas of the specific gravity map. Compared with the bedrock map,

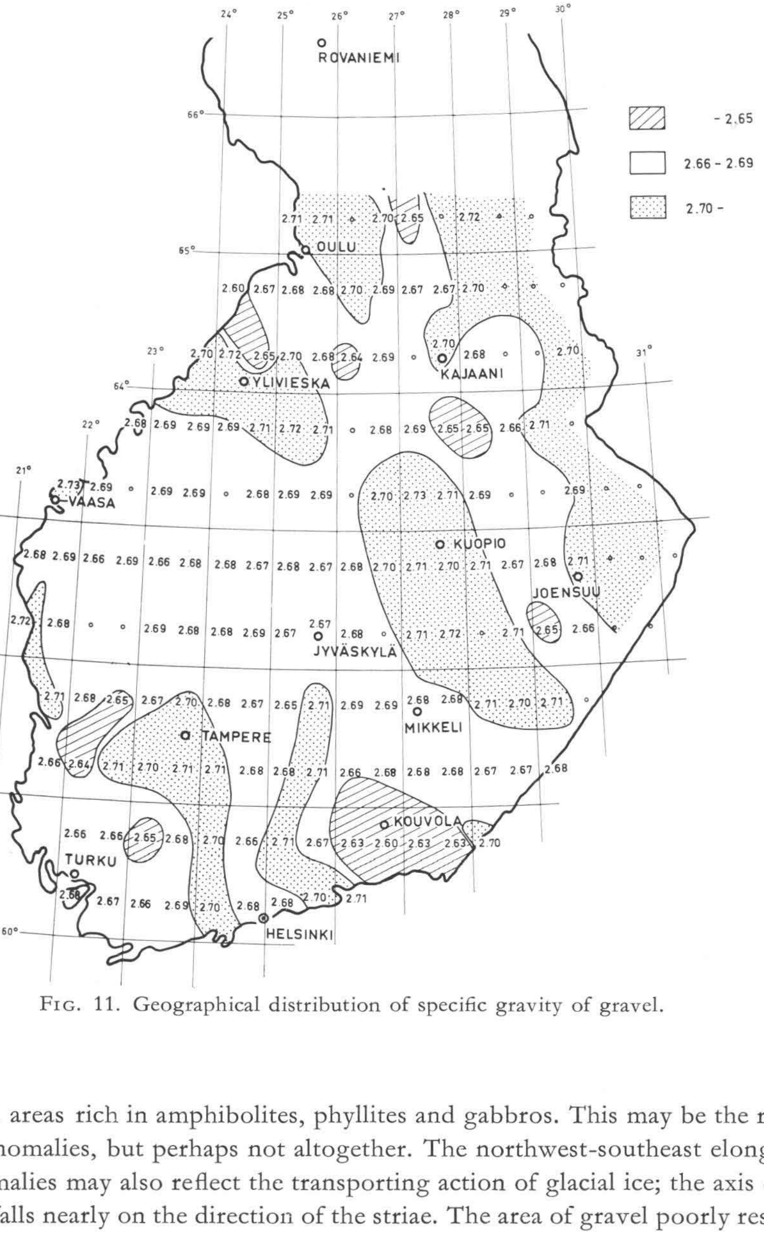


FIG. 11. Geographical distribution of specific gravity of gravel.

they lie on areas rich in amphibolites, phyllites and gabbros. This may be the reason for these anomalies, but perhaps not altogether. The northwest-southeast elongation of the anomalies may also reflect the transporting action of glacial ice; the axis of the anomalies falls nearly on the direction of the striae. The area of gravel poorly resistant to abrasion in the southeastern border zone falls on a negative gravity anomaly, but only a curved corner of tough gravel northeast of Ylivieska falls on the positive gravity anomaly.

Figure 14 present the distribution of the mean Swedish impact values (brittleness) of the crushed gravel. It resembles both the specific gravity map and still more that

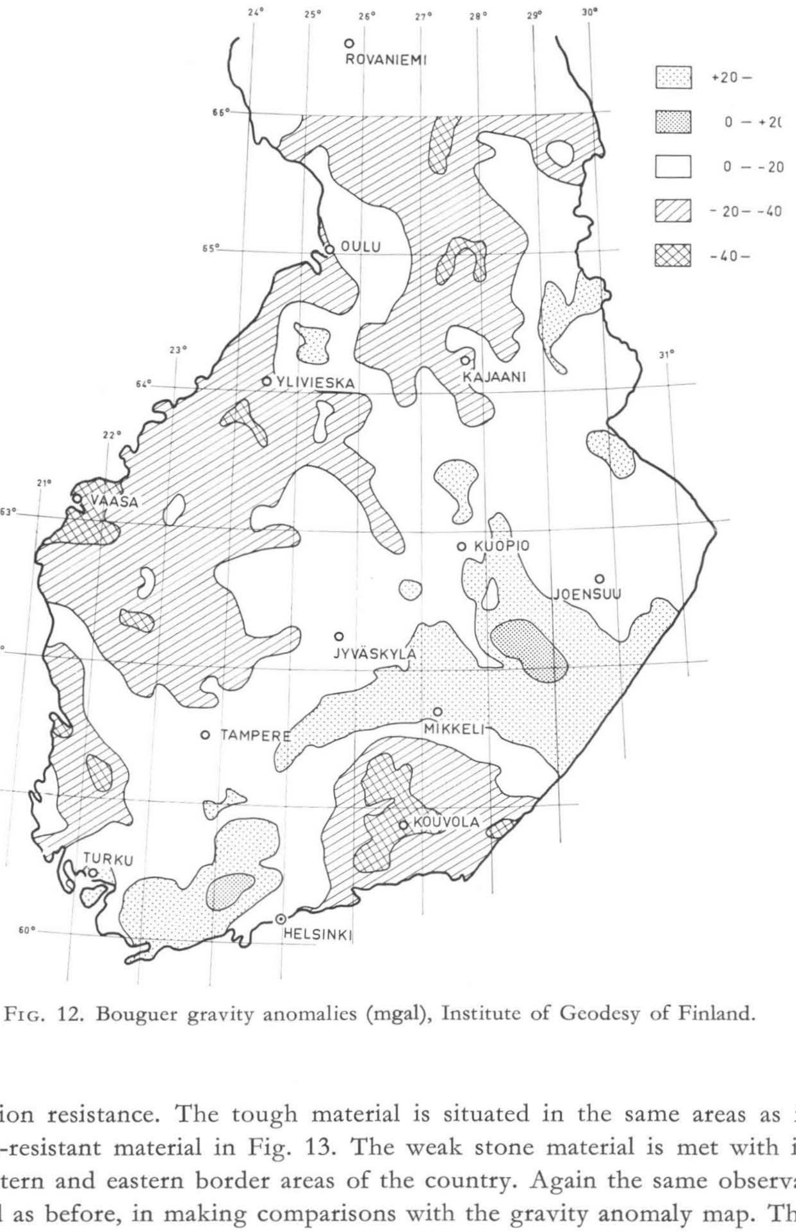


FIG. 12. Bouguer gravity anomalies (mgal), Institute of Geodesy of Finland.

of abrasion resistance. The tough material is situated in the same areas as is the abrasion-resistant material in Fig. 13. The weak stone material is met with in the southeastern and eastern border areas of the country. Again the same observations are valid as before, in making comparisons with the gravity anomaly map. There is a distinct narrow zone of weak material running northsouth from Oulu to the surroundings of Jyväskylä, central Finland. This anomaly cannot be interpreted by comparison with the petrology of the bedrock. It falls partly on the long and narrow Lake Päijänne, which is situated in a fracture zone of bedrock, and the anomaly follows the valley further north along the course of the ancient lake Päijänne and its

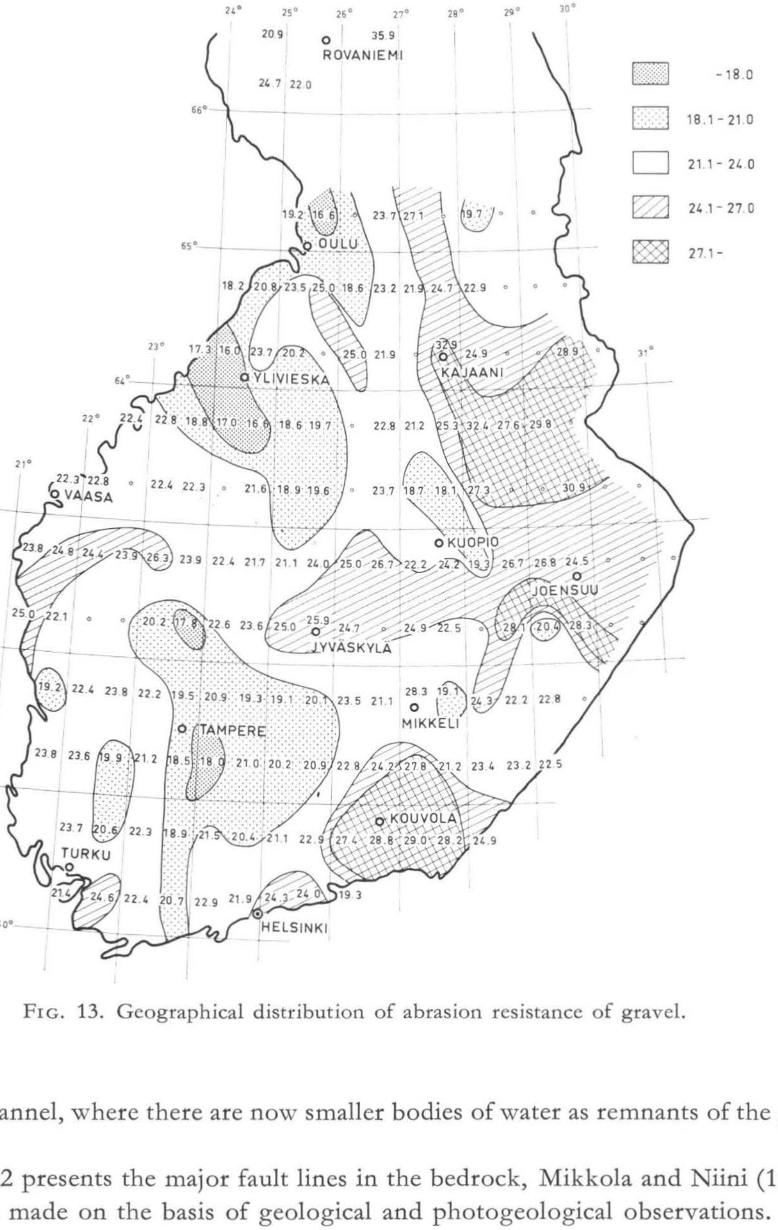


FIG. 13. Geographical distribution of abrasion resistance of gravel.

outflow channel, where there are now smaller bodies of water as remnants of the great lake.

Figure 2 presents the major fault lines in the bedrock, Mikkola and Niini (1968); the map is made on the basis of geological and photogeological observations. This map shows neither the detailed fracturing of the bedrock nor the areas of intensive tectonic disturbances, but the number of fault lines still gives a picture of the tectonization of the country. The same fault lines are presented is statistical form in Fig. 15, which may be easier to compare with the strength anomaly maps. This tectonical map better resembles the maps showing the strength of crushed gravel

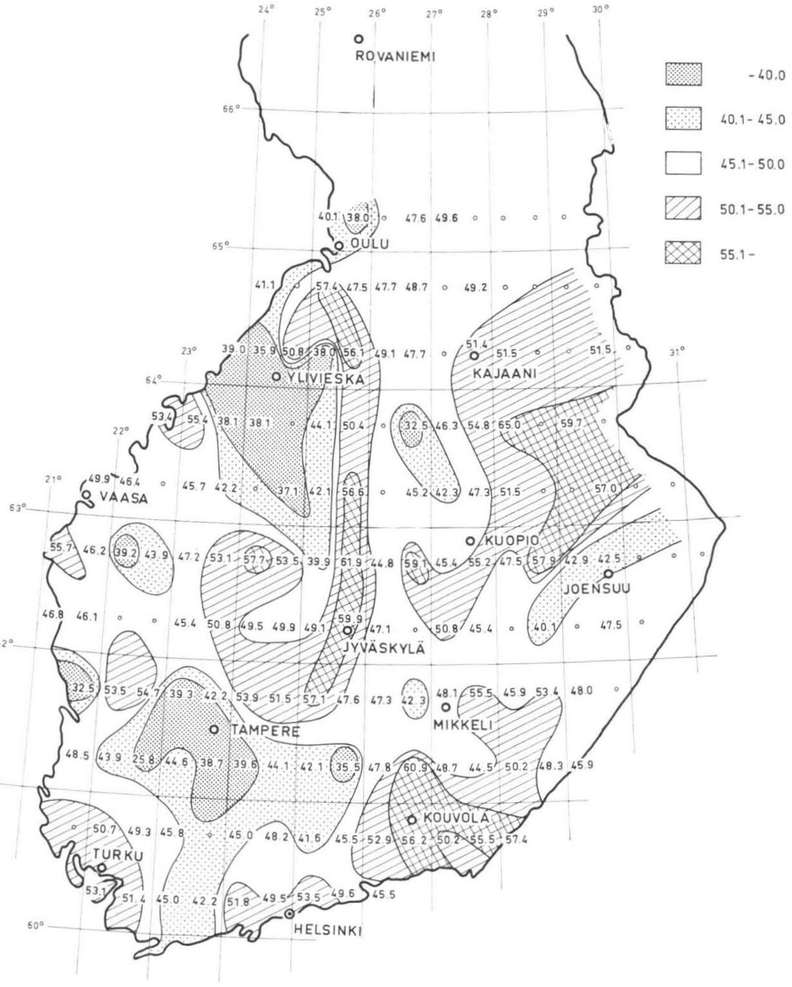


FIG. 14. Geographical distribution of brittleness of gravel.

than does the map of the bedrock, although the specific gravity map, which may be assumed to be a simplified presentation of the bedrock petrology, closely resembles the strength maps. The close regional correlation of brittleness of gravel and fracturing of bedrock shows that the forces which led to the faulting of bedrock also caused the internal stresses and cracking of mineral grains (cf. Paulmann 1966). The regional properties of bedrock are reflected in the nature of gravel in bulk as well as in the properties of the smallest stones in gravel.

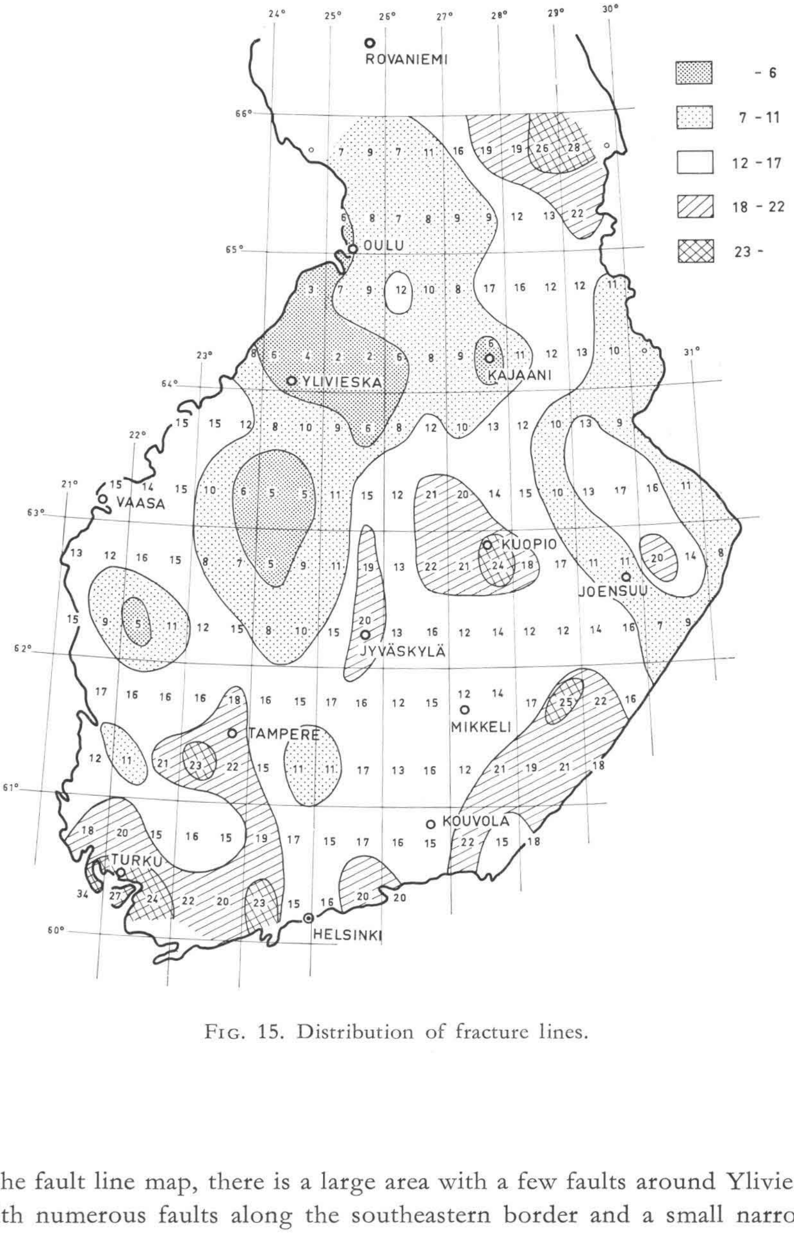


FIG. 15. Distribution of fracture lines.

In the fault line map, there is a large area with a few faults around Ylivieska, an area with numerous faults along the southeastern border and a small narrow area with many faults close to Jyväskylä. All of them agree well with the strength maps. However, the agreement is not complete. For there is also an area with a few faults along the eastern border of the country, which falls on an area of weak stone material and an area with many faults in the neighbourhood of Tampere, which falls on the area of strong stone material.

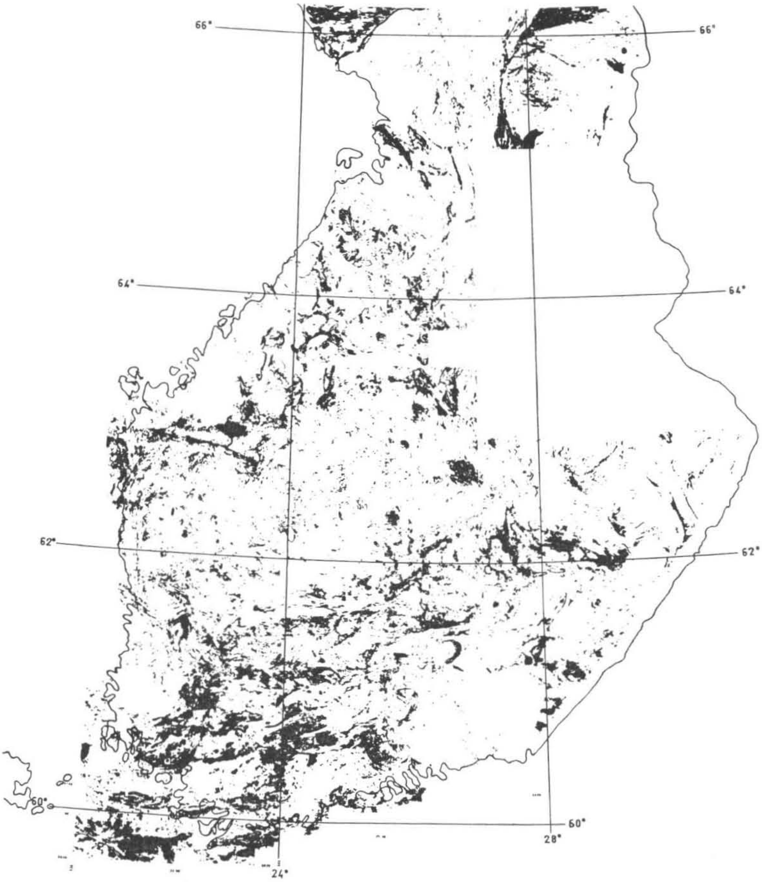


FIG. 16. Aeromagnetic total field anomalies, Geological Survey of Finland.

The aeromagnetic vertical anomaly map (Fig. 16) made by the Geological Survey of Finland shows both the distribution of basic igneous and metamorphic rocks, like gabbro and amphibolite, and also that of pyrrhotite containing phyllites. The first two rock varieties are tough while the third is weak. Phyllites of this kind are mostly met with in the Karelian schist belt of eastern Finland but also in the area northeast of Vaasa. The greatest thrust faults are also seen in this map as geophysical accidents (Paarma 1964). The strength maps closely resemble this anomaly map, too. Especially the anomaly reaching from Tampere southwards may be interpreted by means of the magnetic anomalies showing the distribution of amphibolites.

It must be stated that neither the petrology nor the tectonics of the bedrock alone can show the distribution of strength of the stone material, but they must both be

TABLE 29

Correlation of regional distribution of the properties of gravel and bedrock

	L.A.	Sw.i.	gravity	faults
sp.gr.	—0.31	—0.32	—0.27	0.10
faults	0.04	0.16	—0.31	
gravity	0.04	0.01		
Sw.i.	0.51			

taken into account when considering the reasons for the strength anomalies. Furthermore, effect of transportation by glacial ice is reflected in the elongated form of the anomalies.

The conforming of the regional distribution of the strength of gravel and fault number and gravity of bedrock in the maps presented was studied by calculating the Pearson correlation coefficients of the mean values of properties in the rectangles. The result is given in Table 29.

In the chapter dealing with the strength of different rock types, the correlation of strength values is shown to depend on petrology. It also depends on local geology, or, it might be better said, on the common effect of petrology and tectonics.

The correlation coefficients of the technical properties of crushed gravel material from different Road Building Districts are given in Table 31. Those of specific gravity and strength values are also presented along with the regression coefficients, in Table 30.

The correlation coefficients of the strength values vary from 0.35 to 0.75, all being positive. The greater the strength values (weaker stone materials) are, the greater would seem to be the angle of the regression line. The correlation coefficients of strength and specific gravity are negative and rather small.

TABLE 30

Dependence of correlation of strength values of crushed gravel on regional differences (*r* = Pearson correlation coefficient, *q* = linear regression coefficient)

District	L.A./Sw.i.		L.A./sp.gr.		Sw.i./sp.gr.	
	r	*q*	*r*	*q*	*r*	*q*
Uusimaa	0.50	0.23	—0.28	—28.4	—0.41	—91.4
Turku	0.46	0.20	—0.26	—19.4	—0.02	—02.8
Häme	0.45	0.18	—0.29	—26.5	—0.30	—69.0
Kymi	0.48	0.23	—0.31	—20.5	—0.19	—26.8
Mikkeli	0.35	0.12	—0.12	—14.2	—0.09	—29.9
Kuopio	0.67	0.37	—0.40	—68.3	—0.31	—96.7
Keski-Suomi	0.37	0.16	—0.11	—11.4	0.06	—14.2
Vaasa	0.39	0.14	—0.01	—01.5	—0.11	—34.5
Oulu	0.70	0.30	—0.34	—22.3	—0.10	—21.6
Lappi	0.75	0.62	—0.51	—74.2	—0.43	—76.2
Kainuu	0.39	0.17	—0.24	—28.7	0.19	52.2
Pohjois-Karjala	0.64	0.22	—0.44	—54.2	—0.16	—57.9
Keski-Pohjanmaa	0.64	0.23	—0.18	—15.5	—0.21	—51.4

TABLE 31

Correlation and regression coefficients of the technical properties of crushed gravel in different districs of Finland

1	a	b	c	d	e	
a	1	0.50	— 0.11	— 0.22	— 0.28	
b	0.2	1	0.19	0.19	— 0.41	
c	— 4.1	16	1	0.44	0.03	
d	— 3.0	5.7	0.2	1	0.33	
e	—28	—91	0.1	2.5	1	

2	a	b	c	d	e	
a	1	0.46	— 0.02	0.26	— 0.26	a
b	0.2	1	0.39	0.40	— 0.02	b
c	— 0.7	32	1	0.38	0.14	c
d	4.3	15	0.18	1	— 0.01	d
e	—19	—28	0.3	— 0.07	1	e

3	a	b	c	d	e	
a	1	0.45	0.01	— 0.05	— 0.29	
b	0.2	1	0.34	0.37	— 0.30	
c	0.5	34	1	0.27	0.06	
d	— 0.6	13	0.1	1	— 0.09	
e	—26	—69	0.1	— 0.6	1	

4	a	b	c	d	e	
a	1	0.48	— 0.09	— 0.35	— 0.31	a
b	0.2	1	0.25	— 0.002	— 0.19	b
c	— 2.6	16	1	0.35	0.09	c
d	— 5.4	— 0.1	0.2	1	0.12	d
e	—20	—27	0.2	0.5	1	e

5	a	b	c	d	e	
a	1	0.35	0.06	0.34	— 0.12	
b	0.2	1	0.44	0.45	— 0.09	
c	1.9	45	1	0.35	— 0.11	
d	3.3	13	0.1	1	— 0.11	
e	—14	—30	— 0.4	— 1.3	1	

6	a	b	c	d	e	
a	1	0.67	— 0.16	0.15	— 0.40	a
b	0.4	1	0.14	0.36	— 0.31	b
c	—13	20	1	0.21	0.20	c
d	2.5	11	0.1	1	0.01	d
e	—68	—97	0.4	0.1	1	e

7	a	b	c	d	e	
a	1	0.37	— 0.14	0.13	— 0.11	
b	0.1	1	0.48	0.40	— 0.06	
c	— 8.3	69	1	0.41	0.12	
d	2.0	15	0.1	1	0.09	
e	—11	—14	0.2	0.6	1	

8	a	b	c	d	e	
a	1	0.39	— 0.08	0.18	— 0.01	a
b	0.1	1	0.22	0.48	— 0.11	b
c	—20	19	1	0.11	0.21	c
d	1.9	14	0.04	1	— 0.09	d
e	— 1.5	—35	0.8	— 0.9	1	e

9	a	b	c	d	e	
a	1	0.70	— 0.41	— 0.18	— 0.24	
b	0.3	1	— 0.16	0.001	— 0.10	
c	—24	—22	1	0.47	0.33	
d	— 2.8	0.02	0.1	1	0.39	
e	—22	—22	0.5	2.4	1	

10	a	b	c	d	e	
a	1	0.75	— 0.24	— 0.42	— 0.51	a
b	0.6	1	0.05	— 0.10	— 0.43	b
c	— 2.0	5.1	1	0.71	0.23	c
d	— 9.8	— 2.9	0.2	1	0.40	d
e	—74	—76	0.4	2.5	1	e

11	a	b	c	d	e	
a	1	0.39	— 0.18	— 0.18	— 0.24	
b	0.2	1	— 0.16	0.16	0.19	
c	— 9.6	—20	1	0.22	0.09	
d	— 2.5	4.8	0.1	1	— 0.10	
e	—29	52	0.2	— 0.9	1	

12	a	b	c	d	e	
a	1	0.64	— 0.22	0.10	— 0.44	a
b	0.2	1	— 0.09	0.24	— 0.16	b
c	—13	—15	1	0.35	0.20	c
d	1.5	10	0.1	1	— 0.25	d
e	—54	—58	0.4	— 2.1	1	e
	a	b	c	d	e	

13	a	b	c	d	e	
a	1	0.64	— 0.25	0.38	— 0.18	a
b	0.2	1	0.02	0.49	— 0.21	b
c	—12	2.2	1	0.20	0.04	c
d	4.5	16	0.1	1	— 0.40	d
e	—16	—51	0.1	— 2.9	1	d
	a	b	c	d	e	

a = abrasion resistance (L.A. value), b = impact strength (Sw.i. value), c = flakiness, d = elongation, e = specific gravity, 1 = Uusimaa, 2 = Turku, 3 = Häme, 4 = Kymi, 5 = Mikkeli, 6 = Kuopio, 7 = Keski-Suomi, 8 = Vaasa, 9 = Oulu, 10 = Lappi, 11 = Kainuu, 12 = Pohjois-Karjala, 13 = Keski-Pohjanmaa.

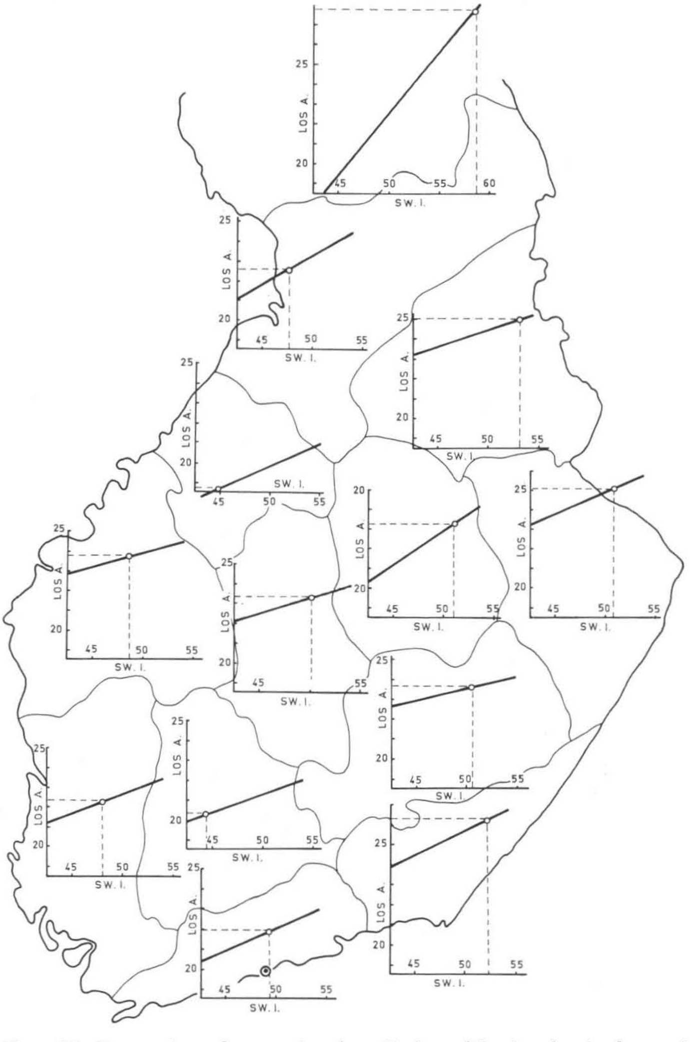


FIG. 17. Regression of strength values (L.A. and Sw.i. values) of gravel in different Road Building Districts. O = arithmetic mean of values.

When the linear regression functions are formed the arithmetic means of the properties can be taken from Fig. 7. Regression lines of strength values of different districts are presented in Fig. 17. According to Table 14 the regression coefficients of strength values in igneous rocks are smaller than those in metamorphic rocks. The strength value regression line thus also reflects the amount of igneous or metamorphic rocks in the gravels of the district. For example in the gravel of Kuopio district metamorphic rocks and of Keski-Suomi igneous rocks predominate.

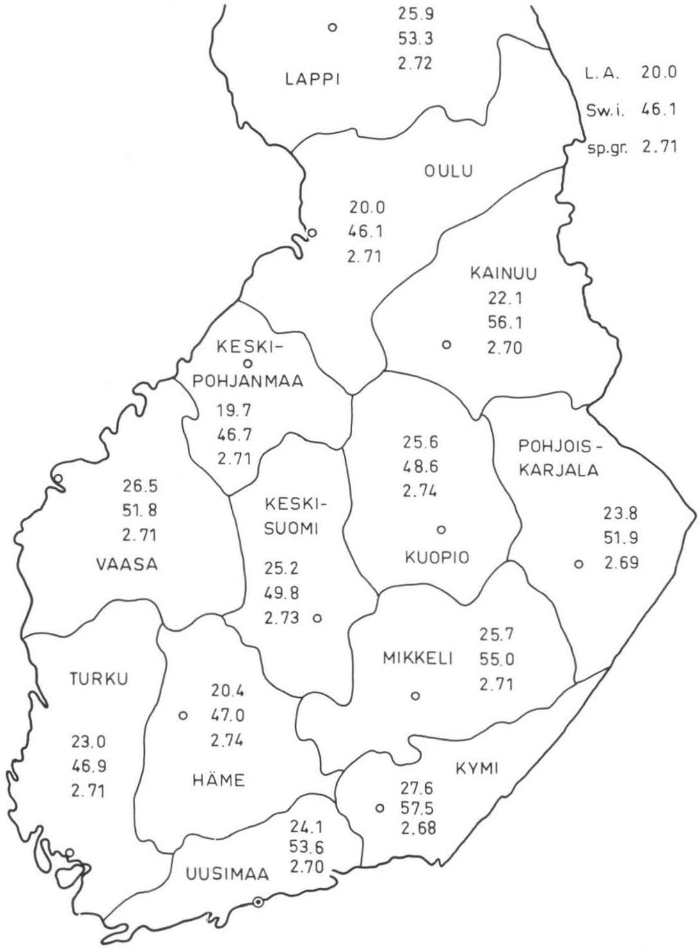


FIG. 18. Mean abrasion resistance, brittleness and specific gravity of bedrock materials of different Road Building Districts.

Macadam

The macadam samples included in this study represent only the site of their origin. Yet, the mean values of their properties may give an idea of the regional geological features.

The heaviest macadam material (Fig. 18) comes from the Häme and Kuopio districts and the lightest from the Kymi district. The heaviest gravel was met with in the Keski-Pohjanmaa district (see Fig. 10).

The weakest macadam samples come from the Kymi district and the toughest from the Keski-Pohjanmaa district. The weakest gravel, again comes from Lapland.

In Lapland, where the center of the continental ice sheet stood, a thick mantle of weathered bedrock was left in places. The crushing action of the moving ice mass had been much less marked there than in the southern parts of Finland. This is still apt to be reflected in the nature of the gravel, which contains partly weathered material from the upper part of bedrock. The macadam samples studied had not undergone weathering, the material for road building having been chosen with this in view. The glacial till in Lapland contains more weathered material than the tills occurring in central and southern Finland (e.g. Kauranne 1957). Eskers contain the same material, transported and sorted by glaciofluvial streams which ground most of the weak material to finer fractions of drift, but the partly weathered material seems to have been left also in the largest grain sizes of gravel.

When the strength values of crushed gravel and macadam material of various districts are compared, it becomes apparent that in every district except Lappi the crushed gravel is tougher than the macadam.

Yet, it might be assumed that the stones and gravel particles of glaciofluvial deposits are sound, inner cores of boulders and stones enriched by natural crushing forces. In the macadam over 5 % of the samples have a specific gravity of over 2.80, in gravel only 0.6 %. This must be due to the crushing of basic rock varieties by natural forces (Kauranne 1970). The material of heavy rock types is found in the finer fractions of the drift (Soveri & Hyyppä 1966). It might also be assumed (Okko 1967) that the glacial erosion of hard rock varieties composing hills had been greater than that of valleys consisting of faulted and weathered rocks (cf. Niini 1968), thus reflecting in the composition of gravel.

Figure 19 shows the distribution of the mean specific gravities of the macadam in the various rectangles. The differences are quite small. The area near Kouvola of light material is due to rapakivi in the bedrock. There is also heavier than average material situated in the neighbourhood of Ylivieska, resembling that in crushed gravel (see Fig. 11). Heavy material likewise occurs in the vicinity of Tampere and to the south as well as between Jyväskylä and Kuopio, where it has the features of the material of crushed gravel.

Figure 20 presents the mean Los Angeles values obtained for macadam material. The same anomaly features as appear in the map showing the Los Angeles distribution of values for crushed gravel (see Fig. 13) are to be seen here. There is another area of weak material reaching from Vaasa southeastwards. This may be caused by the light gray, coarse-grained, weak Vaasa granite, which occurs on both sides of the Bothnian (Svecofennian) schist belt (see Fig. 1). The dark gray, coarse diorites west of Jyväskylä also come out as a smaller area of weak material. Coarse and medium-grained (loose) mica gneisses likewise influence the aspect of the map, causing an area of weak material around Kuopio.

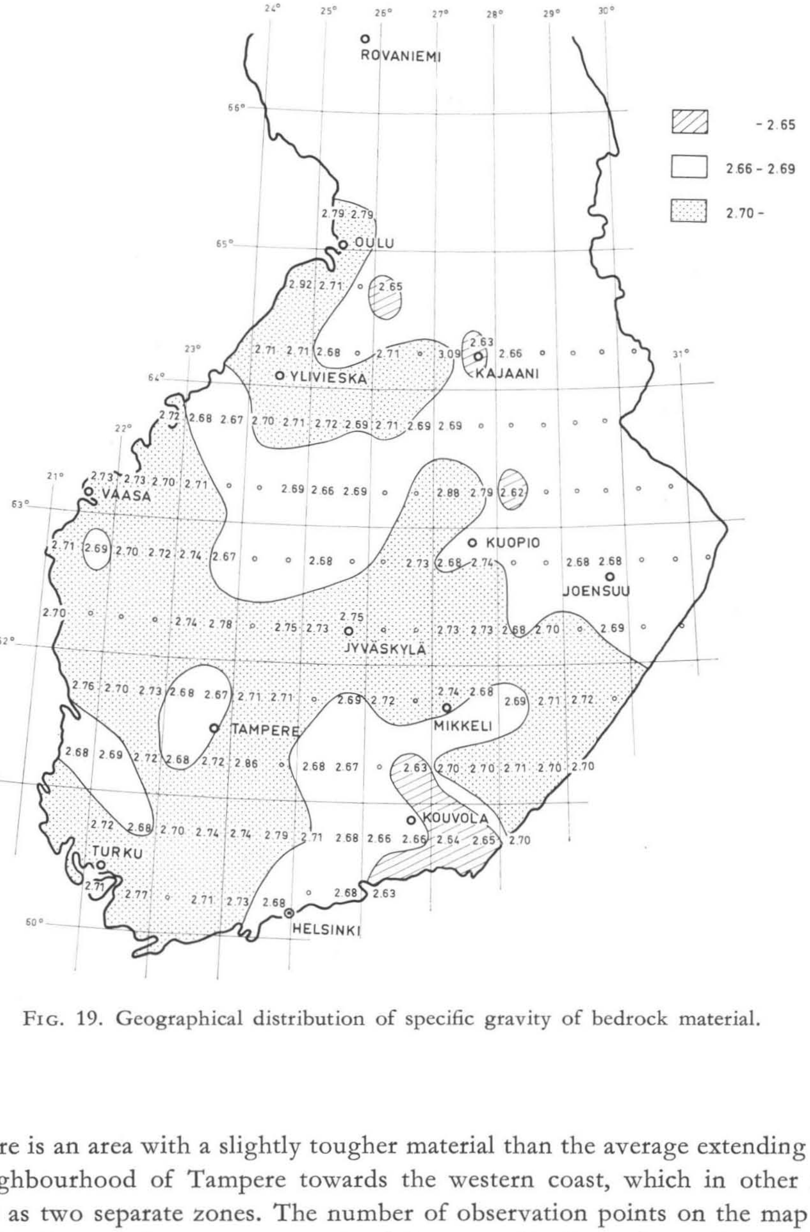


FIG. 19. Geographical distribution of specific gravity of bedrock material.

There is an area with a slightly tougher material than the average extending from the neighbourhood of Tampere towards the western coast, which in other maps appears as two separate zones. The number of observation points on the map is so small that the way they are connected and the anomalies formed must largely be left to the imagination.

Figure 21 presents the mean Swedish impact values of macadam material. This picture closely resembles that of abrasion resistance, there is even the small area of tough material southeast of Mikkeli. A corresponding area close to Tampere

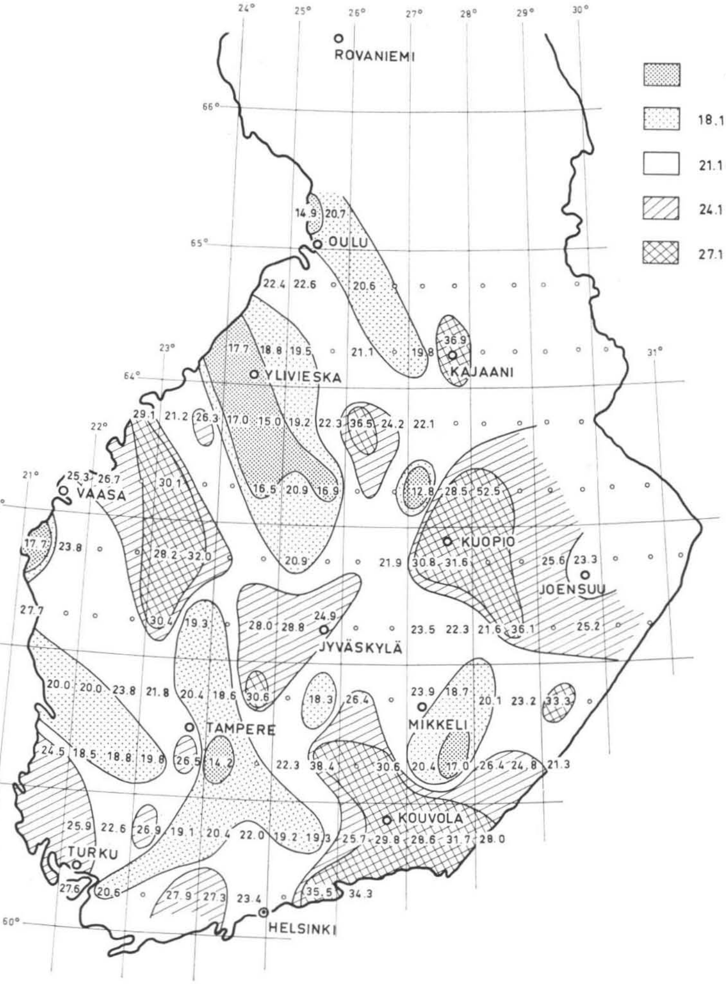


FIG. 20. Geographical distribution of abrasion resistance of bedrock material.

lies some 50 km farther west; this feature resembles that shown by the distribution of brittleness of crushed gravel (see Fig. 14).

It may be stated that the maps representing the brittleness of crushed gravel and macadam and the maps representing the abrasion resistance of crushed gravel and macadam are more alike than are the maps representing the abrasion resistance and brittleness of macadam and the ones representing the abrasion resistance and brittleness of crushed gravel. Thus it is not only the type of material but the kind of toughness which determines the strength distribution.

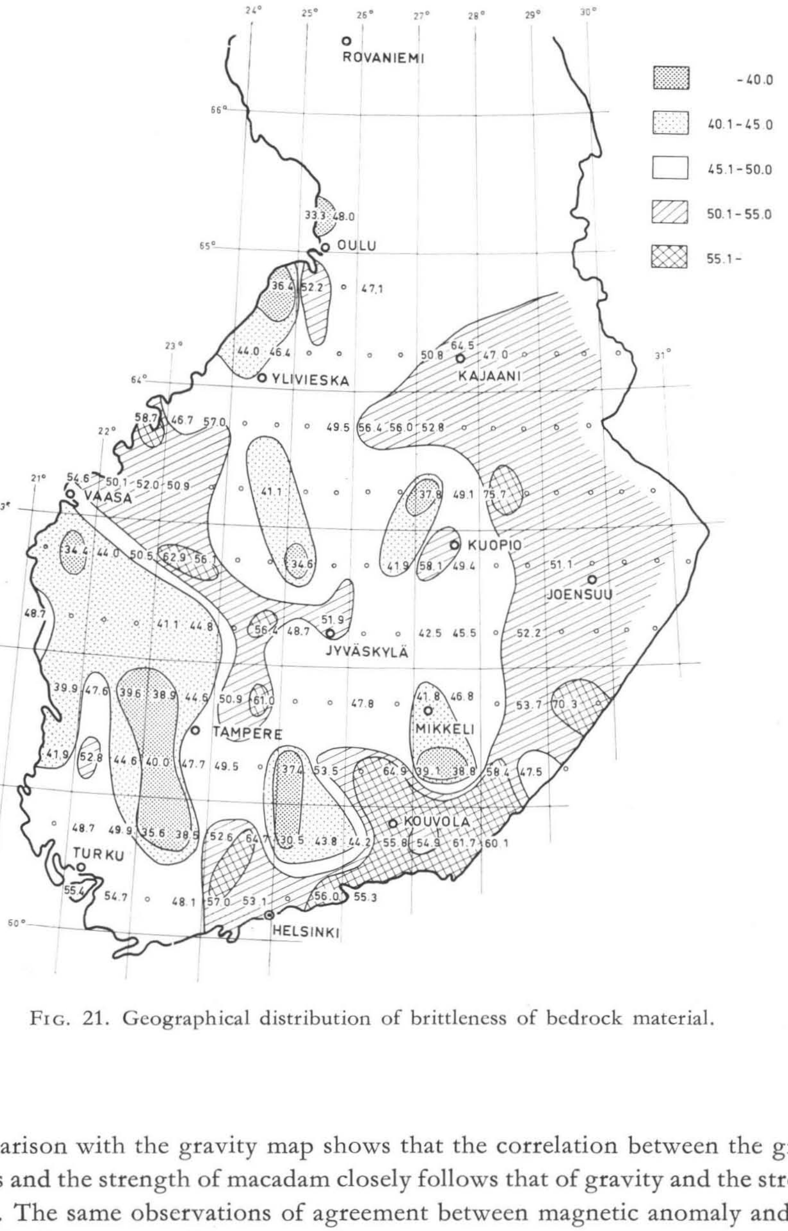


FIG. 21. Geographical distribution of brittleness of bedrock material.

Comparison with the gravity map shows that the correlation between the gravity anomalies and the strength of macadam closely follows that of gravity and the strength of gravel. The same observations of agreement between magnetic anomaly and fault line distribution maps and the macadam strength maps may be made as in case of crushed gravel.

The present study did not afford any possibility for detailed investigation of the transport of glacial debris. The material of the eskers was transported first by glacial ice — perhaps in different directions in several stages (Donner 1953, Kauranne and

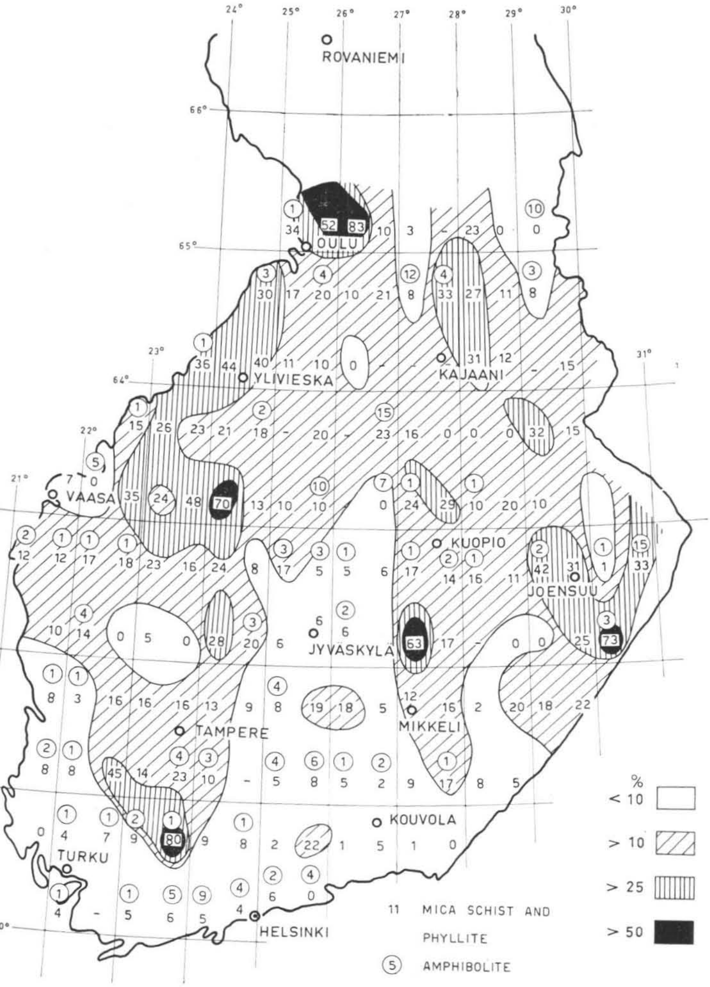


FIG. 22. Mean amount of mica schist + phyllite in percents in the gravel samples of the geographical rectangles, in circles the percentiles of amphibolite.

Tynni 1961, Korpela 1969) and then by meltwater streams. The main part of the material was transported 27 to 47 km, as calculated from the difference between the limits of the anomalies of gravel and bedrock material. The distance the material travelled by the glacial till is on an average only 1 to 5 km (Okko 1941, Kauranne 1959), but some individual rocks may have been transported tens or hundreds of kilometers (e.g. Simonen and Kouvo 1955). The difference in the distance travelled by the glacial till and the esker material washed from it is, according to Hellaakoski (1931), about 5 to 10 km. Matisto (1961) reports that the material composing the

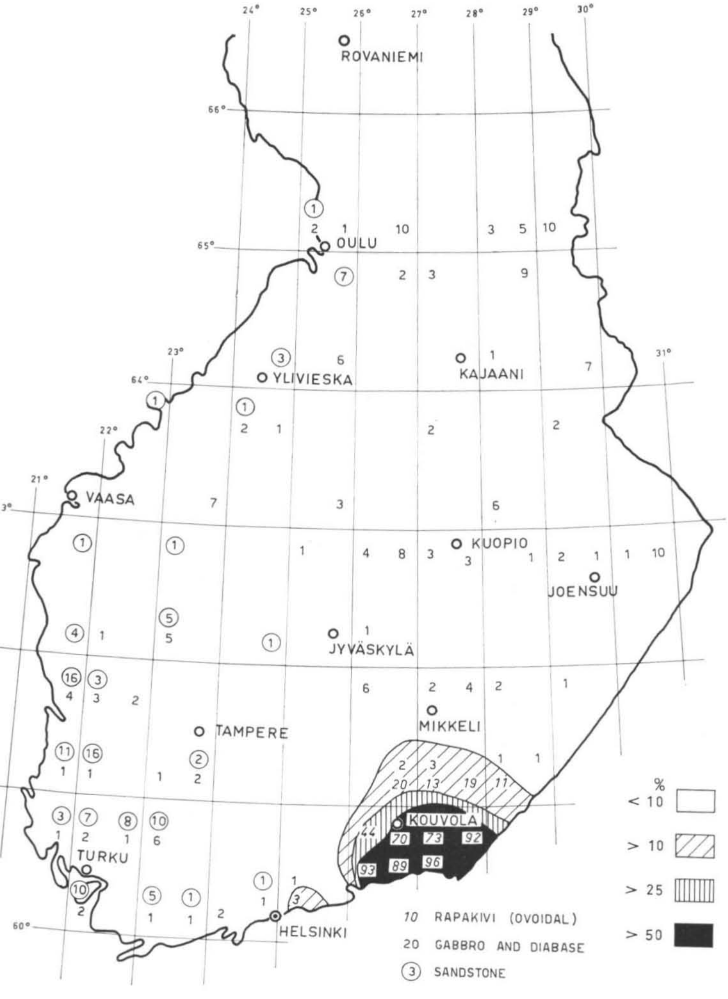


FIG. 23. Mean amount of ovoidal rapakivi (in southeastern border of the country) and that of gabbro + diabase in the gravel samples of the geographical rectangles, in circles the percentiles of sandstone.

eskers west of Tampere was transported from 10 to 14 km, from its source in bedrock, the direction of transport depending on local topography and the distance on the petrological nature of the material. In northern Lapland the transport distance averaged between 25 and 35 km (Mansikkaniemi 1970).

Lithological analysis of crushed gravel samples (fraction 11.3—18 mm) corresponding to stone counts in the field also offers a possibility for the study of transport. Figure 22 shows the mean amount of mica schist and phyllite in gravel samples taken

TABLE 32

Correlation of the regional distribution of the properties of macadam and bedrock

	L.A.	Sw.i.	gravity	faults
sp.gr.	—0.38	—0.21	—0.17	—0.12
faults	0.09	0.14	—0.28	
gravity	—0.03	—0.05		
Sw.i.	0.65			

TABLE 33

Correlation of regional distribution of technical properties of gravel and macadam

Gravel	sp.gr.	L.A.	Sw.i.
Macadam			
sp.gr.	0.31	—0.38	—0.17
L.A.	—0.04	0.45	0.24
Sw.i.	—0.10	0.28	0.36

from the rectangular areas and also the mean amount of amphibolite in them (figures in circles). The mica schists and phyllites (see Fig. 1) were transported south- or southeastwards from their deposits in bedrock. The distance of transport of the mica schists, e.g., south of Tampere, is about 40 km. Figure 23 shows the percentual amounts of ovoidal rapakivi, gabbro and diabase as well as sandstone (in circles). It may be noticed how sandstone was transported from its source around Pori (on the coast west of Tampere) toward the southeast; but sandstones are also met with in considerable amounts along the western coastal area, thus confirming the theory of Veltheim (1962) of the occurrence of sandstones at the bottom of the Gulf of Bothnia.

The factor analysis made of these geographically divided materials did not bring to light any new, sought-after geological factors, but it did produce the already known strength inducing factors, namely that of petrology and that of crushing (Kauranne 1970).

The comparison of the maps by applying Pearson correlation coefficients gave the following results (Table 32).

The correlation of the regional distribution of the properties of gravel and that of macadam were also calculated, the correlation coefficients being given in Table 33.

The values are rather low, although the visual correlation of maps is rather good.

According to Wennervirta (1968), the best method of making comparisons between areas is to calculate the median, the arithmetic mean, the degree of symmetry of the distributions and the correlation coefficients of the properties. This was not done because of the great variation in the number of samples in different rectangles.

SUMMARY AND CONCLUSIONS

The present study is based on the results of aggregate investigations. Materials used for bituminous surfacings are of two different kinds: the macadam blasted directly out of bedrock and the gravel taken from sedimentary deposits. From the over 5 000 samples studied 2 663 were chosen for the present study.

The properties determined in the laboratory are: abrasion resistance (Los Angeles test), brittleness (Swedish impact test), particle form, specific gravity, grain size and lithological or petrological nature of aggregate. The laboratory tests, with the exception of the specific gravity determination, are rather inaccurate, the analytical error varying from ±3 to ±13 % (Kauranne 1970).

The pretreatment, mainly granulation, affects the results. The present study deals only with samples granulated in field crushing plants. The material should therefore be rather homogeneous. The test results were treated statistically to minimize the effect of the analytical error in the drawing of conclusions. Strength and the mineralogy of stone material are directly interdependent. An increase in the feldspar content makes stone weaker. The results of the investigation indicated that also an increase in quartz content tends to have a similar, if slighter, effect. The studies prove that an increasing amount of mica makes stone tougher — which does not mean that it would make it more suitable as aggregate because the intensive cleavage of mica bundles is liable to cause rapid disintegration of bituminous surfacing. The laboratory methods used do not in this respect simulate the strain to which stone material is subjected and do not answer the needs of the study of aggregate durability.

An increasing content of amphiboles makes stone tougher and of calcite, weaker. Increasing porosity makes stone weaker, on the average, but there are also exceptions to this behaviour in the group made up of gabbros and amphibolites. Microscopical study confirms the observations relating to the role of different minerals on the strength of rock.

The microscopical study of the effect of textural properties on the strength of road-building stone yielded the information that rock types with elongated angular grains are tougher than rocks with isometric rounded grains. The other textural properties investigated — grain surfaces, contact mass; alteration, fracturing and orientation — did not have any marked effect on strength. The results of microscopic study as a method of rock strength classification were not encouraging.

The regional distribution of specific gravity in gravel reflects the petrological composition of bedrock: the gravel occurring in areas of coarse rapakivi and granite has a sub-average specific gravity, whereas in areas of abundant gabbros and amphibolites it has an above-average specific gravity. The map representing the specific gravity of macadam may be taken as a simplified representation of the petrology of bedrock. The mean strength of the stone material in areas of above-average specific gravity is greater and, correspondingly, the strength of the material in areas of lower specific gravity is below average. The regional distribution of strength of

material both of sedimentary origin and blasted directly out of bedrock is highly similar, although sedimentary material is somewhat tougher.

Also the map representing gravity and the one of the magnetic vertical field could be comprehended as simplified representations of bedrock petrology. The negative gravity anomaly in the southeastern border zone of Finland conforms with the area of weak material, whereas the high magnetic anomalies extending from Tampere southwards and that in the vicinity of Ylivieska correspond to the areas of tough macadam and gravel. A moderate correlation thus exists between these and the strength maps.

A better correlation nevertheless exists between the strength maps and the map showing the regional number of faults. The area of numerous faults in the southeastern border region, like the region of Central Finland, corresponds to the areas of weak stone, and the area of few faults on the northwestern coast to the area of tough stone material. This points out that the regional stresses and strains of bedrock affect to the smallest units of rock, minerals, and are reflected also in gravel derived from the rock ground of the area.

The coefficients of correlation between mean specific gravities, abrasion resistance, brittleness of both gravel and macadam and fault number or gravity of bedrock of the small rectangular geographical areas are low, although the agreement between the maps is rather good. This shows that the calculation of correlation coefficients does not suit the study of regional distribution correlations.

The location and form of the anomalies in macadam reflects the tectonical and petrological character of bedrock. The difference between macadam and gravel with respect to anomaly form and location depends on the glacial and glaciofluvial transport of the stone material. The distance has been estimated to be some 30 to 40 km southeastwards.

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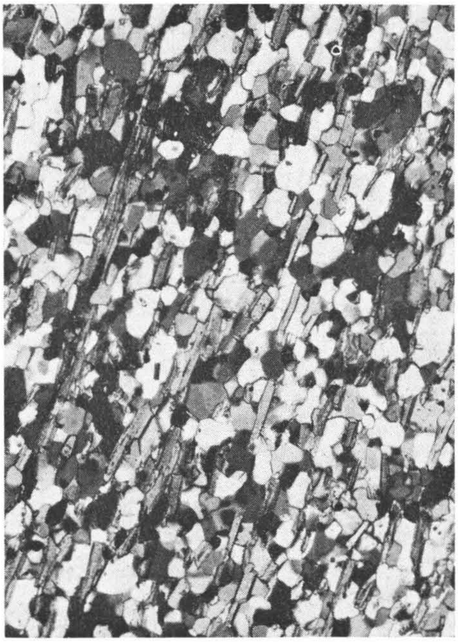
Plates 1 and 2. Microphotos of tested macadams, crossed nicols, magnification 16 x

Key to the plates:

Rock	Sp.Gr.	L.A.	Sw.i.	a	b	c	d	e	n
1. Phyllite, Ylivieska	2.76	15.2	35.3	0.1	2	1	1	3	0
2. Gneiss, Alavieska	2.82	15.4	45.3	0.2	2	2	1	2	0
3. Diorite, Töysä	2.75	14.9	48.6	0.5	3	3	2	2	0.7
4. Granodiorite, Pori	2.77	18.8	30.5	0.4	4	2	3	2	0
5. Amphibolite, Pyhäsalmi	2.71	36.5	56.4	0.1—0.5	5	3	2	4	2.9
6. Rapakivi, Pyhtää	2.62	39.4	77.4	1.0	1	2	2	1	1.1
7. Quartzite, Nilsiä	2.62	52.5	75.7	0.1	1	1	3	1	1.5
8. Granulite, Ivalo	2.76	70.3	88.9	0.5	4	2	2	1	0

a = grain size mm, b = grain-shape index, c = alteration index, d = fracturing index, e = orientation index, n = porosity %.

Rock 1 = isometric quartz (and feldspar), elongated oriented mica.
Rock 2 = slight alteration of feldspar.
Rock 3 = heavy alteration of minerals.
Rock 4 = elongated fractured grains, undular extinction of quartz.
Rock 5 = elongated oriented grains, high degree of porosity.
Rock 6 = large isometric angular grains.
Rock 7 = rounded quartz, sericite mass between quartz grains.
Rock 8 = weakest rock found in Finland.



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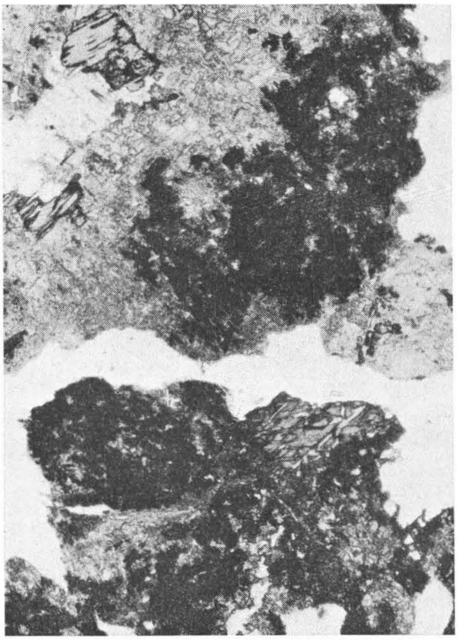

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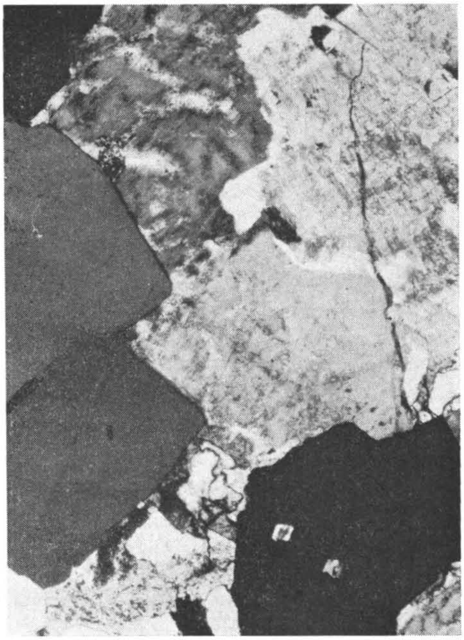

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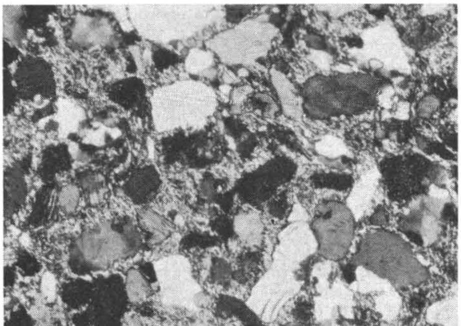

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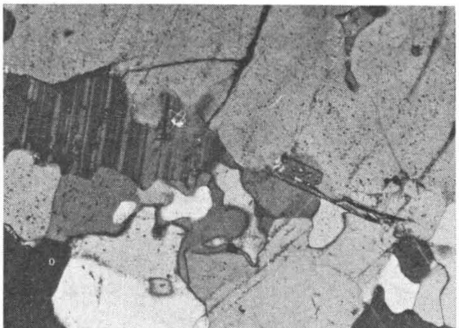

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