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CHARACTERISTICS, PROPERTIES AND QUALITY RATING OF ICELANDIC VOLCANIC AGGREGATES

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ABSTRACT

As the composition of aggregates in Iceland is quite different from most of the neighbouring countries, being almost entirely volcanic, an Icelandic petrographic classification system has been developed. The system is described in some detail. A Petrographic Type, PT is defined as a rock or mineral, usually further specified by the stage of alteration and the porosity of the examined particle. Each PT is assigned a quality factor, depending on either of two different uses, i.e., as a concrete aggregate or bituminous bound aggregate. The factor is 1 (best), 2 or 3 (worst). Another approach to the prediction of the quality of aggregates is presented, in which statistical methods are used to make useful predictive equations based on the percentage of different PTs, and to find the influence of individual Petrographic Types on the properties of interest. By this approach it is hoped that the rather simple and inexpensive test method of petrographic classification will be made much more useful than now. An account is given of abrasion resistance, alkali-aggregate reactivity and freeze-thaw durability of Icelandic aggregates.

INTRODUCTION

Iceland - Island in Icelandic - is a volcanic island surrounded by the North Atlantic Ocean. With a population and area roughly one hundredth of Canada the population density of the two countries is almost equal.

Aggregates are generally taken to be mineral or rock fragments used by man for construction purposes, and more specifically in this paper, as aggregates for concrete and bituminous bound aggregates. In Iceland aggregates are a commercial product mainly came into use in the second half of this century, with a dramatic increase in the fifties with increased concrete house construction, road building and bituminous pavements, and in the sixties with the building of large hydro power plants.

The bedrock of Iceland is overwhelmingly made up of volcanic igneous rocks, especially basalt. Less than 10% is sedimentary and plutonic igneous rock and metamorphic rock is rarely found. A good portion of the aggregates used are quite porous. This composition gives rise to rather special situation, and requires some original Icelandic research. Most of the aggregates exploited are from gravel pits and therefore of heterogeneous composition.

The research that has been carried out in Iceland, relating properties of aggregates to petrography, is mainly found in reports or publications in Icelandic.

Some of it is found in international symposium proceedings and Scandinavian publications (Haraldsson 1984; Johannesson 1986; Petursson 1990).

The purpose of this paper is as follows: 1) To give an insight into the characteristics of aggregates in Iceland with volcanic origin, by discussing a few selected properties. 2) To stress the importance of knowing the petrographical composition with the purpose of being able to predict and/or explain their behaviour (as observed in other tests or in the field).

Comparison of Icelandic rocks and their characteristics to Canadian (Dolar-Martian 1983; Hudec 1983) is not within the scope of this paper.

GEOLOGY AND PETROLOGY

Iceland is like an infant child in the geological family, being some 20 million years old and still in the making. The tectonics and petrology of the country is influenced by its setting: A diverging plate boundary moves relative to a very stable mantle plume underneath; the plume produces primitive basalts similar to the ocean ridge basalts, and at the same time remelts part of the hydrated older crust material, giving rise to more evolved basalt and other volcanic rock types (Oskarsson et al 1985; Steinthorsson et al 1985).
Most of the rocks used for aggregates in Iceland belong to the tholeiitic basalt series of subalkaline volcanic rocks (Irvine and Baragar 1971; Carmichael 1964; Jakobsson 1979). Subsidence and hydrothermal alteration has led to changes in the chemistry and mineralogy of some of the rocks (Kristmannsdottir 1978): this rock is now found at the surface due to erosion. Classical metamorphism, being represented by greenschist facies, has only been found at surface in the south east and in more than 2-3 km deep drillholes (Jakobsson 1979).

PETROGRAPHY AND A CLASSIFICATION SYSTEM

The unusual composition of aggregates has given rise to an Icelandic Petrographic Classification System (Helgason and Guðmundsson 1989). Fig. 1 shows a schematic diagram of the classification procedure.

The PT of an particle is defined as a rock or mineral type, and if needed, further defined by the stage of alteration and/or the porosity and/or other characteristics. The most common rock/mineral types encountered are these: Basalt, basaltic glass, clastic rock, hyaloclastite, tephrite, shell fragments; and in addition by observation in the polarizing microscope, primary minerals (mainly magnetite, olivine, plagioclase, and pyroxene).

When observing the petrographic type, 200 - 400 particles are examined, either by hand, aided by a stereo microscope, or in thin sections using a polarizing microscope.

Before explaining the subdivisions of the PT an imaginary but typical classification is given in Table 1. These results would be based on a macroscopic examination of 5-10 mm particles, giving the percentage of the number of particles. A discussion of the quality rating follows.

<table>
<thead>
<tr>
<th>% of</th>
<th>Petrographic type:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Basalt-unaltered-dense</td>
</tr>
<tr>
<td>2</td>
<td>Basalt-unaltered-porous</td>
</tr>
<tr>
<td>3</td>
<td>Basalt-altered-dense</td>
</tr>
<tr>
<td>3</td>
<td>Basalt-altered-porous</td>
</tr>
<tr>
<td>3</td>
<td>Basalt-highly altered-dense</td>
</tr>
<tr>
<td>2</td>
<td>Andesite</td>
</tr>
<tr>
<td>2</td>
<td>Rhyolite-altered</td>
</tr>
<tr>
<td>3</td>
<td>Amygdales</td>
</tr>
<tr>
<td>2</td>
<td>Basaltic glass-unaltered-dense</td>
</tr>
</tbody>
</table>

+ Quality rating for bituminous bound aggregates
+ Quality rating for concrete aggregates

The alteration stages are four: unaltered, slightly altered, altered and highly altered. Although weathering plays some role in the chemical and mineralogical changes that have taken place, the more important process is hydrothermal alteration at depth. The alteration stages of the petrographical classification system are mainly based on macroscopical observations. A different account, based on detailed analysis of alteration in Icelandic geothermal areas, is given by Kristmannsdottir (1979).

Particles classified as unaltered (sometimes named fresh) bear no evidence of alteration in a macroscopic observation. In slightly altered ones a slight change is observed, olivine phenocrysts and glass groundmass show a beginning sign of alteration: pores in the rock are partly filled with secondary minerals; strength is hardly affected. Altered particles show marked colour change; olivine is altered to clay minerals; metal oxides and glass in groundmass is altered, but plagioclase and pyroxene show little sign of change; pores are usually totally filled; strength is lowered. High alteration leads to further colour change due to almost total alteration of primary minerals and
gloss to clay and some other secondary minerals; total filling of pores; low strength, although in some instances strength and other properties can be improved due to strong alteration products (Gunnarsson 1988).

Pores seen on the surface are defined as being visible holes in the particles that are deeper than their width. Dense rock is not necessarily totally dense, as pores can make up 20% of the surface of a particle. Porous rock has more than 20% of pores, and the width is more than 0.2 mm (usually more than 1 mm). Fine-porous rock is like porous except that the pores are finer than 0.2 mm.

QUALITY RATING

The quality of aggregates may be defined as being the extent to which the properties of it fulfill requirements or specifications. In the Icelandic classification system each petrographic type is quality rated. In line with the above definition of quality, the system allows for different uses of an aggregate, and therefore the quality rating (Q.R.) depends on the use or requirements. At this moment there are two different rating scales in use, one for concrete aggregates, the other for bituminous bound aggregates.

At present, and as a first approach, the quality rating is based on an "educated guess", where each P.T. has been assigned one of three possible values: First class particles (best), second class and third class. Table 2 gives the quality rating for the example in table 1.

Table 2

| (++) Aggregates for bituminous bound pavement | (*) Aggregates for concrete |
| 1. class particles (16%) | 31% |
| 2. class particles (67%) | 58% |
| 3. class particles (17%) | 11% |

Figure 2 shows a print out of petrographic classification results, in Iceland.

In the next chapter a different approach to the question of quality of aggregates will be presented. This is done by using multiple regression analysis to look for the regression of property Y, on petrographic types. X1…Xn. This approach will give an empirically based equation that can be used to predict the behaviour of aggregates.

SELECTED PROPERTIES

Before starting the discussion of individual properties of aggregates, a few words of general nature.

Griffiths (1967) has stated that in the case of sedimentary rock, there are five independent variables, (or properties) of fundamental importance, i.e. the kinds and proportions of elements, m (cf. petrographic type, PT); their sizes, s; shapes, sh; orientation, o and packing, p. Every dependent variable, or an "index", P characterizing the rock (also named behavioral or derived properties) is a function of the five fundamental properties:

(1)

P = f(m, s, sh, o, p)

The theme of this paper is the characteristic of loose material rather than the bound aggregates in concrete or pavements; this means that the orientation, o and packing, p are excluded from equation 1, and the size, s and shape, sh are assumed constant. Therefore equation 1 turns to:
The following discussion focuses on a few chosen properties, with the aim of giving an idea of the relationship between petrographic type and property, \( P \). The relationship of the test-properties to petrographic properties will not be elaborated on.

**Abrasion resistance**

One of the main causes of deterioration of bituminous bound roads in Iceland are the studded tires used by ca. 60% of car owners throughout the 5 or 6 winter months.

Tests for abrasion resistance have been classified into tests for abrasive wear with impact, abrasive wear with pressure and attrition tests (Brown 1981). From the first category the "Los Angeles test" (ASTM 1987) and a pure "impact test" (Statens Vegvesen 1983) are used in Iceland. A close correlation has been observed between these two tests (Haraldsson 1984).

From the group of abrasion tests with pressure, the "Dorn test" is used in Iceland (Petursson 1990). The test procedure (Statens Vegvesen 1983) is adapted from a British method (British Standards Institution 1975). The test is considered to give a good indication of the wear in the field (Petursson 1990). Basically the procedure means wearing 4 x 25 particles of 11.2 - 12.5 mm diameter, by pressing them against aluminium oxide powder on a rotating disk, for a total length along the surface equal to about 120 meters. The pressure is 0.3 MPa. The particles are chosen in concordance with petrographic analysis of the sample and should represent all the common petrographic types in the aggregate. The particles are tested either dry or moist. The weight loss of the particles is measured, and divided by the "bulk density, dry" (Dolar-Mantuani 1983): this gives volume loss of "material" (including voids), reported in cm³.

Table 3 shows results of petrographic classification and various other test results, and will give an idea of the characteristics of different aggregates. The absorption and density (bulk density dry (BD)): tests are done according to ASTM standard test method C 128 (ASTM 1987), with minor changes. Mainly from Petursson (1990). The freeze-thaw test will be explained later.

The Dorn test has usually been performed on dried samples, but as noted earlier, it can also be done on moist samples. Then the particles are moistened by allowing them to equilibrate with air at 95% relative humidity. The difference in test values between the two procedures can be seen in table 3. A general increase in abrasion wear is observed in the aggregates that have an appreciable amount of altered basalt, much more so than for the porous aggregates (Pétursson 1990). This could be due to swelling clay minerals.

The abrasion values do not correlate very well with the quality rating of the petrographic classification system as of today (BD): perhaps no wonder because as noted earlier, the rating used relies as much on personal feelings as test results, and was set some ten years ago.

<table>
<thead>
<tr>
<th>Source Name</th>
<th>Distribution among petrographic types (for 11.2-12.5 mm)</th>
<th>Dorn value: Dry Humid (cm³)</th>
<th>Abs. Density (g/cm³)</th>
<th>Freeze/thaw breakdown (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sediments:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bakkó</td>
<td>16 8 46 4 3 0 18 4</td>
<td>0.57 0.71</td>
<td>3.7 2.55</td>
<td>10.4</td>
</tr>
<tr>
<td>Esjúberg</td>
<td>6 2 77 2 6 0 0 7</td>
<td>0.55 0.71</td>
<td>1.7 2.83</td>
<td>4.7</td>
</tr>
<tr>
<td>Grjótreyvarhæðir</td>
<td>2 0 77 3 4 0 6 8</td>
<td>0.58 0.68</td>
<td>2.7 2.66</td>
<td>5.0</td>
</tr>
<tr>
<td>Haukadalsa</td>
<td>16 1 69 8 4 0 0 2</td>
<td>0.69 0.92</td>
<td>3.1 2.73</td>
<td>18.8</td>
</tr>
<tr>
<td>Hvifailfararsý</td>
<td>8 0 8 3 3 0 4 1</td>
<td>0.47 0.60</td>
<td>2.2 2.81</td>
<td>10.2</td>
</tr>
<tr>
<td>Kolafjörður</td>
<td>55 9 21 2 0 12 0 1</td>
<td>0.51 0.63</td>
<td>2.2 2.78</td>
<td>4.5</td>
</tr>
<tr>
<td>Melar</td>
<td>6 0 73 6 9 0 2 4</td>
<td>0.64 0.94</td>
<td>2.9 2.70</td>
<td>19.3</td>
</tr>
<tr>
<td>Núpur</td>
<td>67 20 9 3 0 1 0 0</td>
<td>0.43 0.48</td>
<td>2.7 2.76</td>
<td>1.2</td>
</tr>
<tr>
<td>Stórar</td>
<td>3 5 53 12 15 2 1 11</td>
<td>0.84 1.08</td>
<td>5.6 2.51</td>
<td>29.5</td>
</tr>
<tr>
<td>Stóra Félssól</td>
<td>0 0 95 1 3 0 0 1</td>
<td>0.53 0.75</td>
<td>2.2 2.78</td>
<td>8.6</td>
</tr>
<tr>
<td>Stóra Laxá</td>
<td>23 10 45 8 1 1 4 8</td>
<td>0.61 0.73</td>
<td>3.9 2.64</td>
<td>9.8</td>
</tr>
<tr>
<td><strong>Bedrock:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Korgúpsstaður</td>
<td>0 0 81 10 8 0 0 1</td>
<td>0.63 0.94</td>
<td>1.7 2.62</td>
<td>4.5</td>
</tr>
<tr>
<td>Snæl</td>
<td>96 0 4 0 0 0 0 0</td>
<td>0.34 0.43</td>
<td>1.1 2.91</td>
<td>0.3</td>
</tr>
<tr>
<td>Vatnafskó</td>
<td>41 57 1 1 0 0 0 0</td>
<td>0.83 0.94</td>
<td>3.6 2.61</td>
<td>2.8</td>
</tr>
<tr>
<td>(Granite, Sweden)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Quartzite, Norway)</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
In order to find a correlation between PT and abrasion, and to obtain a useful prognostic model, it was decided to omit the former quality rating and instead take individual petrographic types into consideration.

The method used for this was the multiple regression analysis, mentioned in the preceding chapter. The analysed data were from commercial tests at the Institute, as well as data from an ongoing research project of Stórhafnafind, an Icelandic bituminous-bound-aggregates committee.

All together 44 tests or cases were analysed. The dependent variable was the Dory value-dry, Dd (cm3) and the independent variables were the petrographical types (% of total no of particles). After observing the distribution of the different Pts II was decided to include the following types in the analysis: Basalt-unaltered-dense, Buad; Basalt-unaltered-porous, Buap; Basalt-altered-dense, Bad; Basalt-altered-porous, Bap; Basalt-highly altered, Bha and all the rest of the types were put in a single variable, Diverse particles, Div.

The computer programs used for the analysis belong to a statistical package (SPSS 1988) that has a multiple linear regression module. The best equation found involved a natural logarithmic transformation of all the variables, and by using stepwise methods the following equation evolved:

\[(3) \quad \ln Dd = -0.67 \\
- 0.06 \times \ln (Buad + 1) \\
+ 0.20 \times \ln (Buap + 1) \\
- 0.12 \times \ln (Bap + 1) \\
+ 0.18 \times \ln (Bha + 1)\]

or, after inversion:

\[(4) \quad Dd = 0.51 \times (Buad + 1)^{-0.06} \times (Buap + 1)^{0.20} \\
\times (Bap + 1)^{-0.12} \times (Bha + 1)^{0.18}\]

Of the total variation in Dd the explained variation amounts to 73% and the results are highly significant (99.9%).

To visualize the goodness of fit, the observed and the predicted Dory abrasion values are plotted in figure 3. The figure shows a departure from the linear relationship between the two values at the high end of abrasion; the two aggregates with Dd values above 1.4 are mainly made of highly porous particles, and should probably be classified as fine-porous basalt or even tuffa, rather than porous basalt. (NB The values in table 3 and the values used to compute the regression curve are not exactly the same, so they are not fully comparable.)

In addition to the prognostic aspect of the statistical analysis, there is a causal phase. As we assume that the abrasion is directly influenced by each of the six different petrographic types, the correlation coefficient for each of the pairs of Dd and PT, see table 4, should give a good idea of the relative importance of each PT. The same statistical program was used as before, and the names of variables are unchanged.

Table 4

<table>
<thead>
<tr>
<th>Correlation coefficients.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dd</td>
</tr>
<tr>
<td>ln Dd</td>
</tr>
</tbody>
</table>

It is concluded that the statistical methods employed can be used to make useful predictions of Dory abrasion value-dry based on petrographical test results. More cases should be included in the data pool, but according to these first results Basalt-unaltered-porous has by far the most influence on the dry abrasion. (As noted earlier, the change in test conditions from dry to humid seems to affect the altered particles the most; the effect on the correlation coefficients remains to be analysed.)

Alkali-silica reactivity

Alkali-silica reactivity has caused extensive damage in Iceland. Cement manufactured in Iceland from 1958 is of high-alkali type (Na2O equivalent ≥ 1.3%). Since 1980 silica fume has been added to it for counteraction, first as 5% replacement and later 7%, and from that time no damage has been observed. A general review of the damage and of remedial measures is found in Kristjansson and Olofsson (1990).
No detailed account of the reactivity of Icelandic aggregates and individual petrographic types will be given here; such an account remains to be done. Research in Iceland in this field has been scarce, but based on it and recent foreign research some conclusions can be drawn: 1) The most common types of reactive particles are of “intermediate” to “acidic” composition, i.e. andesite (andesite), dacite and rhyolite, (frequently with a more or less glassy groundmass) (Thalow, N. 1976; Olafsson 1989). 2) Some basalts may be reactive, notably oversaturated, or quartz-normative, tholeite, although no case of damage due to it has been confirmed in Iceland (Katayama and Kaneshige 1987; Shayan and Quick 1988; Katayama et al. 1989).

That rocks of intermediate to acidic composition give most of the problems encountered in Iceland seems to be substantiated by the fact that all the cases of severe damage occur where this type of material is a part of the aggregate; on the other hand, in a detailed survey of concrete houses in a town where the concrete aggregate is only made of unaltered basalt and unaltered basaltic glass and no damage due to alkali-aggregate reactivity could be found (Kristjansson 1979; Kristjansson and Olafsson 1990).

This was set out to verify in an earlier investigation (Helgason 1982). Rock samples from the tholeitic series were collected (except for Icelandite) and tested. The results are presented in figure 4. It shows the expansion of mortar bars, made according to ASTM C 227 (ASTM 1987), with high-alkali cement. Unaltered, porous olivine tholeite basalt was taken as innocuous aggregate, and to it were added other rock types to test their reactivity and the percentage proportion. Much to the author’s surprise, not only the dacite and rhyolite tested showed a great deal of reactivity, but also a tholeitic basalt. In view of the recent foreign research noted earlier, the reactivity of the quartz normative tholeitic basalt tested is believed to be due to reactive silica minerals and interstitial glass.

As a conclusion, intermediate and acidic rocks are thought to be responsible for the majority of damage due to alkali-aggregate reaction in Iceland, but oversaturated basalt probably plays some role too. The proposed theory of alteration and hydration of basaltic glass as a major source of reactivity of Icelandic aggregates (Gudmundsson and Atgeirsson 1975) is questioned.

Freeze-thaw durability

In Iceland freeze-thaw durability is a very important property of aggregates, due to the many freeze-thaw cycles and the wet climate. In Reykjavik about 50 cycles occur each year. Due to rain and snow and de-icing, streets in Reykjavik are wet 80% of the wintertime. A thorough study of these and other aspects of freeze-thaw durability in Iceland has been done by Steinunnaférd (1990), a committee on bituminous bound aggregates (see also Petursson 1989).

A new test method has been proposed by the Committee. Particles of the size 2.4 - 4.8 mm and/or 9.5 - 12.5 mm are tested. After vacuum saturation in a 1% NaCl solution, 2 * 400 g of material is tested for 72 freeze-thaw cycles, each lasting 2.4 hours with a temperature amplitude of +/- 4°C. The results are presented as the percentage, F, of the total material that has broken down to sizes below 1.2 mm and 4.8 mm respectively.

Results of an identical test (+/−4°C) by the committee are shown in Table 3. These results, and others done for commercial purposes, were analysed with the same statistical methods as described in the chapter on abrasion resistance (Helgason and Gunningardtt 1990). This time 9 independent variables were included in the analysis. The results were highly significant (99.5%), but a smaller amount of the variation was explained by the regression or 55%. The form of the equation, after inversion is this:

\[ F = 2.72 \times (\text{Bad + 1})^{-0.3} \times (\text{Bho + 1})^{-1.4} \]

The variables in the equation used for the prediction of freeze-thaw durability are Basalt-altered-dense, Basalt-highly altered, and Rhyolite. The analysis was continued when more data has been collected. This first analysis indicates alteration to be more influential in freeze-thaw durability than macroscopic porosity (ibid.).

CONCLUSIONS

1. The unusual composition of aggregates in Iceland has necessitated the creation of a new petrographic classification system, with regard to use in building construction, different from international, standardized systems.

2. The most important criteria in defining the petrographic type of basaltic rock, is the stage of alteration.

3. Theoretically it should be possible to predict the behaviour or property of aggregates once their petrographic composition has been determined. The paper shows practical examples of this.

4. Instead of assigning rather inflexible stepwise quality rating or factor for each petrographic type, and to
use them to classify the aggregates, it is considered more appropriate to predict the aggregates' behavior directly from the petrographical types, with the aid of statistical analysis.

5. Abrasion resistance of aggregates, as measured by the Dorni test, seems to be mainly influenced by the porosity in the case of dry particles, whereas the degree of alteration also plays an important part when the samples are moist.

6. In the case of alkali-aggregate reactions, andesite, dacite and rhyolite are considered the most damaging in Iceland, but quartz-normal basalt has the potential of deleteriousness.

7. The stage of alteration, and to a lesser degree porosity, seems to govern freeze-thaw durability of Icelandic aggregates.

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REFERENCES


