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Assessing soil index parameters to determine the frost susceptibility of crushed rock aggregates

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ABSTRACT

In Norway, crushed rock aggregates are widely used in all layers of pavement infrastructures. Frost heave severely affected the Norwegian road network during cold winters of 2009/10 and 2010/11, including newly built roads. In 2016, the Frost Protection for Roads and Railways project (FROST) was set up in part to investigate frost susceptibility and frost heave of crushed rock aggregates. Twenty-three frost heave tests were performed on the 0–4 mm fraction with nine types of different rock, in which 2 series were measured at different crushing stages in a production line. The tests succeeded to expand knowledge on the frost susceptibility of crushed rock aggregates, using the segregation potential as frost susceptibility criterion. However, the cost and time necessary for laboratory work were important. Since budget for road construction and rehabilitation are variable, a methodology to estimate the segregation potential using soil index properties was tested. A laboratory investigation was carried out to compare segregation potentials determined in laboratory ($SP_{0\ lab}$) to those calculated using the normalized segregation potential equations ($SP_{0.n}$), which requires only four soil index parameters: the specific surface area of the fine fraction, the mean grain-size diameter of the fine fraction, the water content, and the liquid limit of the fine fraction, the fine fraction being <75 μm. Results showed a good correlation between the $SP_{0\ lab}$ and the $SP_{0.n}$. Results also showed a strong correlation between the $SP_{0\ lab}$ and the crushed rock aggregates with a specific surface area of the fine fraction of <8 m^2/g, which was the case for 19/23 samples. High specific surface area estimations (≈12.5 m^2/g) found in early stage crushing aggregates are believed to be cause by weak mineral content enrichment and/or grain-surface irregularities in the fine fraction. In conclusion, this study confirms that the estimation of the segregation potential of a crushed rock aggregate from the normalized segregation potential equations is possible and reliable. The relationship developed using the specific surface area to determine the segregation potential is promising and should be validated furthermore to reinforce the relationship.

1. Introduction

Crushed rock aggregates (CRA) are widely used in roads and railways in Norway and have replaced natural gravel as the main source of aggregates materials for three reasons: i) the depletion of available natural gravel resources, ii) stable production i.e., easiest quality control and iii) mechanical performance. In general, CRA are stiffer and less subjected to permanent deformation than natural gravel. Sand and gravel production has therefore decreased by approximately 50% from the 80's to the 90's and remained stable since 2000's at around 14 million tons/year; 27% used in road construction divided in 17% in unbound layers and 10% in asphalt production. On the other hand, CRA production increased by approximately 100% between 2000 and 2015, with 67 million tons being produced in 2015 (Mineralressurser i Norge 2015, 2016). 50% of CRA were used in the road construction industry; 34% in unbound layers and 16% in asphalt production. Sweden and Finland are also progressively replacing gravel material with CRA, due to resources becoming scarce (pers. disc. Gustavsson, 2019). The research on crushed rock aggregates therefore considered as relevant for Northern countries.

The cold winters of 2009/10 and 2010/11 severely affected the Norwegian road network. Frost heave affected a large portion of the transport infrastructure system, including newly built roads (Statens Vegvesen rapporter, 2012). Several conclusions were drawn from this experience. One was that a strict, empirical frost design is not applicable

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Table 1
Norwegian frost susceptibility classification (modified from N200, 2018).

Frost susceptibility	Class	Material <22,4 mm		
		Mass %		
		< 2 µm	< 20 µm	< 200 µm
Non/ Negligible	T1	–	< 3	–
Low	T2	–	3–12	–
Moderate	T3	>40[1)]	> 12	< 50
High	T4	< 40	> 12	> 50

1) Soils with more than 40% of <2 µm are considered as moderately frost susceptible (T3).

to all pavement structures situations. Requirements were therefore amended (Statens Vegvesen rapporter, 2013), but the frost susceptibility still uses an empirical criterion.

It is well accepted that frost heave can occur when 3 conditions are met: i) water availability, ii) sub-freezing temperatures and iii) a frost susceptible soil/CRA (Chamberlain, 1981). Natural soils have been widely studied in the past and still are today. There are, however, relatively few studies in the literature about CRA's frost susceptibility. The CRA used in base layers (0–20 or 0–31.5 mm) were the most widely studied due to their importance regarding bearing capacity. More knowledge about frost susceptibility of CRA is therefore needed for the base, but also for all other layers (sub-base, frost protection layer, draining layer…).

Frost susceptibility criteria in Norway are qualitative and were adapted by Nordal in the sixties from Casagrande's work (1931) that conclude: "*under natural freezing conditions and with sufficient water supply, one should expect considerable ice segregation in non-uniform soils containing more than 3% of grains smaller than 0.02 mm, and in very uniform soils containing more than 10% smaller than 0.02 mm*" (cited by Chamberlain, 1981). It has been verified that a grain-size based criteria help for the identification of non-frost susceptible material (Kaplar, 1974), and the Norwegian Public Roads Administration (NPRA) still uses this criterion in its latest road construction handbook (Håndbok N200, 2018). Table 1 presents the different Norwegian frost susceptibility classes based on particle size distribution.

The experience of NPRA shows that thick road pavement used for main road construction (up to 2.4 m thick), kept the frost front within the road CRA layers, limiting the magnitude of frost heave to a negligible amount. However, this effectiveness has its inconvenient: it is very expensive to build in this way. In Norwegian secondary roads, the frost heave and frost depth must be limited as much as possible (Håndbok N200, 2018), but there are no heaving magnitude estimations that are calculated. To be in accordance with this approach, there is a need to move from a rigid-empirical design to a science-based approach, in which the effect of input parameters can be calculated.

From an engineering point of view, different project levels requires different data precision. E.g., a highway will require highly reliable data while a local rural road can be designed using estimated values. Frost heave tests produce highly reliable data. However, those tests require sophisticated and costly equipment, and are time consuming, especially for large samples. Construction and rehabilitation of secondary roads are constrained by financial limitations. Cold climate countries such as the Nordic countries and Canada have large roads and railways networks, the majority covering long distances in sparsely populated territory (Doré and Zubeck, 2009). More than 70% of roads in Norway are secondary roads with an average annual daily traffic (AADT) of less than 1500 (pers. disc., Skoglund 2019). The frost design of these roads must therefore be optimized considering limited budgets, i.e., that the frost susceptibility estimation of the different soils and geo-materials must be cost-effective and reliable.

In 2016, the Frost Protection for Roads and Railways project

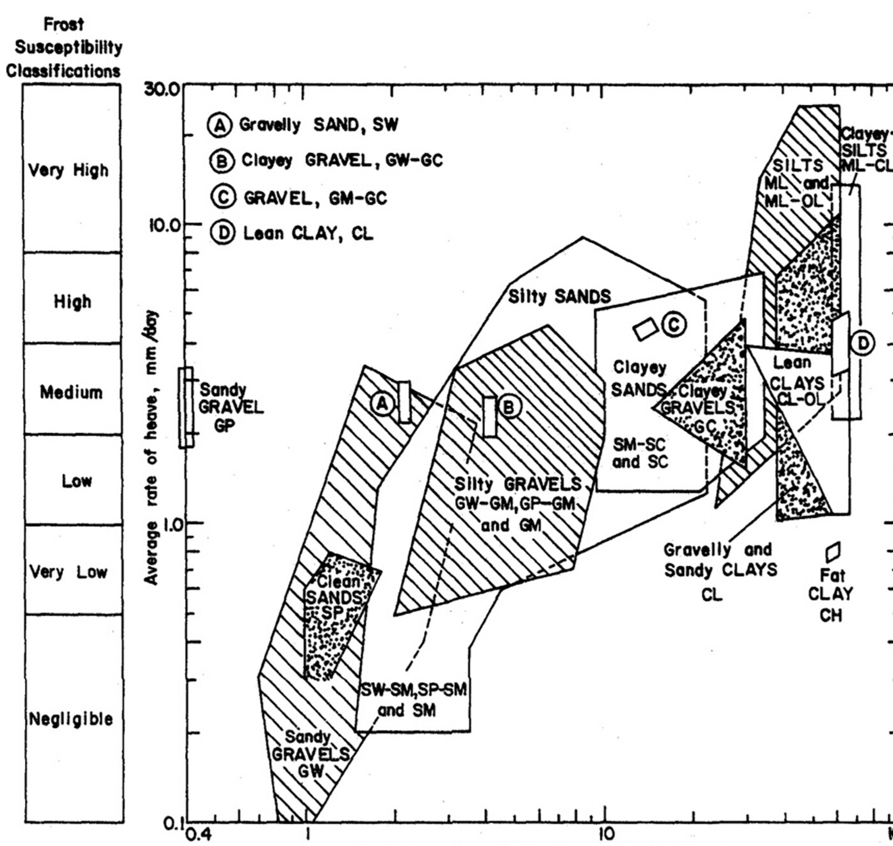

Fig. 1. Frost heave rates and classification of remolded soils (U.S. Army Corps of Engineers, 1984).

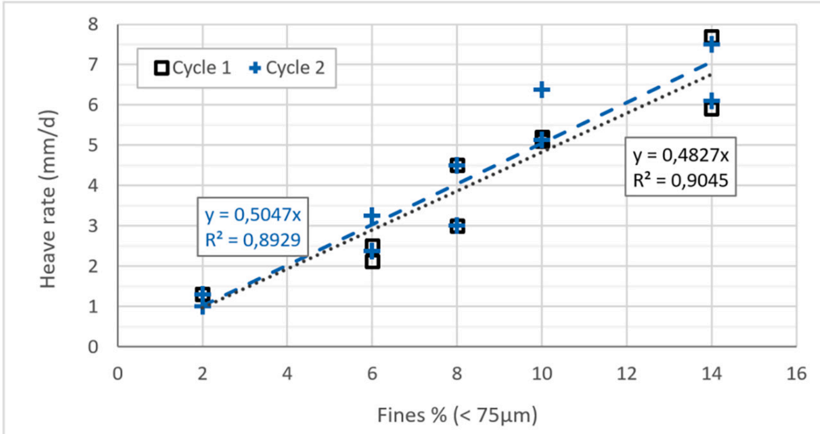

Fig. 2. Frost heave rate as a function of fine content % < 75 μm for granular base materials 0–20 mm crushed limestone (adapted from Tester and Gaskin, 1996).

(FROST) was set up in part to investigate frost susceptibility and frost heave of crushed rock aggregates. The segregation potential (SP), a mechanistic parameter developed by Konrad and Morgenstern (1981) was chosen for frost susceptibility criterion. The segregation potential allows frost heave magnitude to be estimated in field conditions (Saarelainen, 1992).

This paper present the comparison between the SP measured in laboratory and the SP estimated from soil index properties (Konrad, 2005) for crushed rock aggregates. In details, the sections presented are: 1) a literature review of frost susceptibility estimation for crushed rock aggregates (CRA), 2) the methodology for determining frost susceptibility using soil index properties, 3) the investigation of laboratory SP_0 ($SP_{0\ lab}$) and SP_0 estimated from the normalized SP ($SP_{0.n}$) and 4) a discussion of the results, variability, and limitations of the method.

2. Literature review

The freezing behaviour of soils and granular materials is influenced by many factors; particle size distribution, mineral composition, water content, density, degree of compaction/consolidation, permeability, capillarity, availability of water, temperature conditions (magnitude, freezing period length, temperature gradient), and local climate variability (Konrad, 1999; Brandl, 2008).

The frost susceptibility of low fine content crushed rock aggregates (CRA) was proven negligible to low (Federal Highway Administration, 2017) but a relatively medium-high fine content will make them frost susceptible. The particle size upper limit of fine varies from <80 μm in Canada, < 75 μm in USA and < 63 μm in Europe. The fine content percentage that is accepted by different transportation administrations varies quite significantly (Chamberlain, 1981). Some agencies combine fine content limitation criterion with other material characteristics criteria such as plasticity index (e.g., U.S. Army Corps of Engineers, 1984), capillarity (e.g. Finnish Transport Infrastructure Agency), and mineralogy (e.g. Austrian Federal Road Administration) to name a few. Fig. 1 presents the average rate of heave as a function of % passing 0.02 mm (20 μm) of different soils/ aggregates (USCS classification), and their associated frost susceptibility classification (U.S. Army Corps of Engineers, 1984). The figure illustrates the large variation of heaving rates for different materials, e.g., the frost susceptibility of a well graded gravel (GW) with 2% passing 0.02 mm varies from negligible to medium. Fine content limitation of <20 μm from Casagrande (1932) is still in use in the Norwegian road construction handbook N200 but its determination needs a fine particle size analysis (e.g., hydrometer) which is not always performed.

Frost susceptibility criteria using particles size therefore have flaws. Frost susceptibility and heave magnitude estimations can vary significantly for a given fine content, making it hazardous to apply in a project design scenario.

Table 2
Austrian mineral criterion (Brandl, 2008).

Maximum allowable percentage < 0.02 mm (by mass)	Mineral composition of the grains < 0.02 mm
3%	Determination of mineral components is not necessary.
5%	Standard case: Additional tests are not necessary if the mineral composition, or the material behaviour under freeze-thaw conditions (in the field or in the laboratory) respectively, are known from earlier investigations.
5%	In case of materials whose characteristics are unknown: 1) Non-active minerals 2) Mixture of 1) and a maximum of a) 10% kaolinite group b) 30% chlorite group c) 30% vermiculite group d) 40% montmorillonite group e) 50% mica group Marginal condition: mixture of 1) and a maximum of a) 60% mica group + chlorite group b) 50% mica group + chlorite group + kaolinite group c) 50% mica group + kaolinite group d) 40% mica group + chlorite group + kaolinite group + montmorillonite group Further mixtures, not listed here, of laminated silicates are allowable up to a total sum of a maximum of 40%. If this limit value is exceeded, freezing-thawing tests are necessary. 3) Freezing-thawing tests should be performed, if an intensive reddish-brown colour of the material indicates that iron hydroxides are contained.
8%	Non-active minerals, with maximum of 1% by mass < 0.002 mm.

Tester and Gaskin (1996) performed an investigation on crushed limestone using the CRREL II frost heave test (Chamberlain, 1987). They varied the fine content <75 μm from 2 to 14% in a 0–20 mm granular limestone base material. Their study showed that the rate of frost heave increased linearly with % of fines (Fig. 2). The results show that a CRA

Table 3
Frost susceptibility classification in use by the MTQ, Quebec, Canada (St-Laurent, 2006).

Frost-susceptibility	SP	Frost heave rate	Frost heave ratio
	$mm^2/^{o}C \cdot d$	mm/d	$\Delta h/h_{frozen}$ (%)
Negligible	<12	<0.5	<1
Low	12–35	0.5–2	1–4
Medium	35–75	2–4	4–8
High	75–200	4–8	8–20
Very high	>200	>8	>20

needs to have <8% of <75 μm fines to have a low frost susceptibility according to CRREL 1987 reviewed classification, i.e., to have a frost heave rate of ≤4 mm/day (which was 2 mm/day in the CRREL 1981). Each sample was tested in two successive tests (cycle 1 and cycle 2) as specified in the CRREL II standard. It was found that the results from multiple cycles on crushed limestone were very similar.

Cwiakala et al. (2016) tested a 0–31.5 mm CRA base layers. He found a poor correlation between frost susceptibility and fine contents % of <75, < 20 and less <2 μm. He also found that there was a divergence when he assessed frost susceptibility using the plastic limit, plasticity index and sand equivalent.

Uthus (2007) concludes that a particles size criterion gives useful information on the qualitative classification of the frost susceptibility of a CRA. However, the study showed significantly different heave rates for almost equally graded gneiss. It was also observed that water was sucked in the unfrozen layer below the frost front during a freezing test.

Brandl (2008) stated that the Casagrande criteria was too strict and uneconomic. He proposed a mineral composition criterion, currently used by the Austrian road authorities. It was shown that some minerals in the fine fraction <63 μm are more frost susceptible than others. The mineral composition criterion proposes to vary the maximum allowable % of <0.02 mm fraction depending on its mineral content such as kaolinite, chlorite, vermiculite, montmorillonite, and mica groups. Allowable % of different mineral composition are presented in Table 2.

Konrad and Morgenstern (1981) developed the segregation potential (SP) to characterize frost susceptibility and frost heave magnitude of soils. The SP is defined as a linear relationship between water velocity intake (υ) and the thermal gradient (∇T) in the frozen fringe when steady state is reached (Eq. (1)).

$$SP = \upsilon/_{\nabla T} \tag{1}$$

The SP is mainly in function of parameters such as soil type, porosity, overburden pressure, over-consolidation ratio, suction, and unfrozen water content, to name a few (Konrad, 1999). Empirical relationships to estimate the effect on the SP according to those parameters' variation were relatively well developed for fine grain soils (Konrad, 1999). The SP_0 was defined as the segregation potential at zero overburden pressure. It is correlated to SP (or SP_{field} or SP_t in some papers) using Eq. (2) (Konrad and Morgenstern, 1982).

$$SP = SP_0\, e^{-a\,Pe} \tag{2}$$

where a is a sensibility parameter to overburden pressure (MPa^{-1}) and P_e is the overburden pressure (MPa). The SP allows the estimation of heaving magnitude in field conditions, and is expressed in $mm^2/^{\circ}C \cdot d$ or $mm^2/^{\circ}C \cdot h$. The SP has so far been implemented in the SP-2D model (Konrad, 1994), and in the SSR model (Saarelainen, 1992) used in CHAUSSEE2 software (St-Laurent, 2006), the latest being use by the Quebec Ministry of Transportation (MTQ) in Canada since it's development. Table 3 presents the CHAUSSEE2 frost susceptibility classes and their associated SPs, frost heave rate and frost heave ratio (St-Laurent, 2006). Frost susceptibility classes range from negligible to very high.

Rieke (1983) used the effective specific surface area to estimate the SP of sand, silt, and clay mixtures. The difference between the specific surface area and effective specific surface area is that only external grain surfaces are considered in the latest, i.e., without clay interlayer surfaces. Rieke investigated the role of fine fraction nature by replacing partly the <75 μm sand fraction by silt, poorly crystalized kaolinite, well crystalized kaolinite, and montmorillonite clays. He showed the important role of the mineral content of the fine fraction on frost susceptibility. Rieke (1983) also concluded that the permeability of the frozen fringe depends upon the thickness and the unfrozen film's adsorbed water on the soil grain surface. Unfrozen water can be directly linked to specific surface area (Ss), as demonstrated by Zunker (1928, cited by Beskow, 1935), Dillon and Andersland (1966) and Anderson and Tice (1972), (all cited by Rieke, 1983). The specific surface area can therefore be used as a measure of the permeability of the frozen fringe. Rieke demonstrated that the effective surface area was related to the segregation potential (SP_0). Results for mixtures of sand and 5, 10 and 20% of silt and poorly crystallized kaolinite are presented in Fig. 3.

Similar work was carried out by Konrad and Lemieux (2005), who tested the effect of mineral content in the fine fraction of a granitic 0–20 mm base layer. They tested different granitic fine content (5, 10 and 15% of <80 μm) and varied proportion of clay in the fine content (10, 50, 75 and 100% of kaolinite). They demonstrated that the SP can be high even at a low percentage of fines, e.g., at 5% fine content composed of 10% of kaolinite and 90% of granitic fines. A set of graphs showing the relationship between frost heave rate and thermal gradient for fine content of 5, 10 and 15% containing 10, 50 or 75% of kaolinite clay was presented. The SPs for different fine contents and kaolinite fractions were also presented. Frost heave rates and SPs were increasing with fine content increases and the kaolinite clay proportion in the granitic fine fraction had a major effect in frost susceptibility of the 0–20 mm base course.

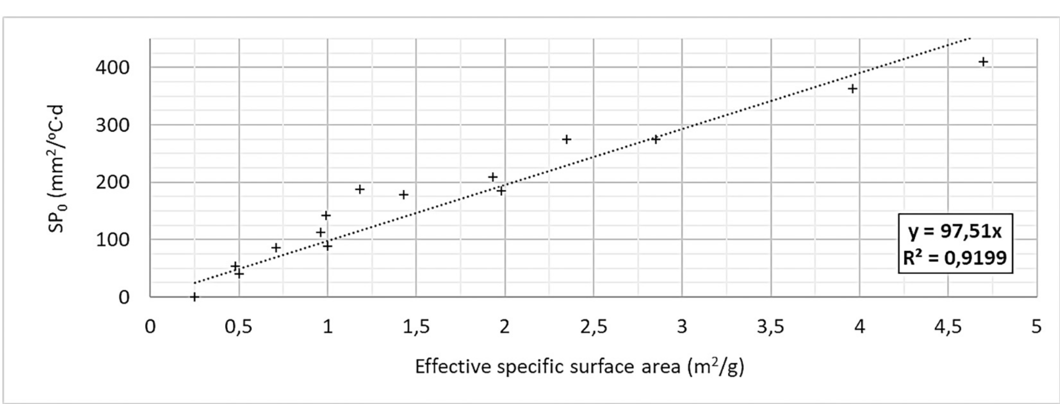

Fig. 3. Segregation potential of sand mixed with 4, 10 and 20% silt and poorly crystallized kaolinite clay according to effective specific surface area (modified from Rieke, 1983).

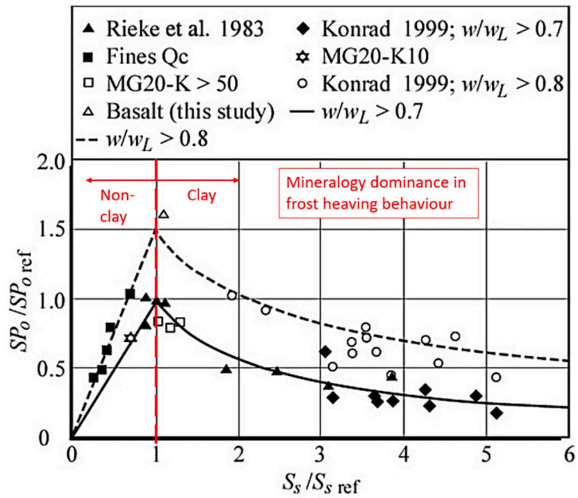

Fig. 4. Normalized segregation potential (SP_0 / $SP_{0\ ref}$) as a function of normalized specific surface area (Ss / Ss_{ref}). Fines Qc and Basalt are results for crushed rock aggregates (modified from Konrad, 2005).

Nurmikolu (2005) studied an important number of frost heave tests (> 100) of different 0–31.5 mm crushed rock aggregates ballast used in railway infrastructures. He used the segregation potential to prove that the coefficient of correlation between SP and the fines % is improved when using % < 2 μm instead of % < 63 μm. It was observed that the there was a good correlation between the <20 μm fraction and the SPs of 0–31.5 mm ballast.

Konrad (1999) estimated the SP using soil index properties based principally on the work of Rieke (1983). The specific surface area and the mean particle diameter of the fine fraction <80 μm (d_{50ff}) were included in an empirical relationship and validated for highly frost susceptible glacial till. It was found that shape and mineral content of the fine fraction influenced the unfrozen water content when freezing. Konrad (1999) explained that unfrozen water content can be divided into capillary (or pore) water and adsorbed water. Capillary water can easily move in the soil pores, but not the adsorbed water. The adsorbed water was found to be proportional to the specific surface area. An empirical relationship between d_{50ff} and specific surface area (S_s) for clay-fines related soils has been presented for a ratio of water content on liquid limit (w/w_L) ≈ 0.7 (Eq. (3)).

$$SP_0S_s = \left[116 - 75 log d50_{ff}\right] \times 10^3 mm^4/(^\circ C \bullet s \bullet g) \tag{3}$$

Konrad (2005) tested 6 rock types with their <80 μm fraction (CRA fines) and determined that the SP of CRA fines ranged from medium to very high. A normalized SP was developed from limit values developed by Rieke (1983) and from his previous work (e.g., Konrad, 1999). The normalized SP involved the estimation of an empirical SP of reference ($SP_{0\ ref}$) and an empirical Ss of reference (Ss_{ref}). The relation showed that the normalized SP (i.e., $SP_0/SP_{0\ ref}$) has either a linear relationship with Ss/Ss_{ref} when non-clay fines drive the frost heave behaviour ($Ss/Ss_{ref} < 1$) or has an exponential relationship when it is clay fine driven ($Ss/Ss_{ref} > 1$). The relationship takes different forms depending on the w/w_L ratio (Fig. 4). It was shown that CRA followed the relationship when Ss/Ss_{ref} was <1, as shown by the results for "Fines Qc" (representing the CRA studied by Konrad in 2005) in Fig. 4.

Konrad (2008) performed ramped-freezing tests on 3 base course granular materials (0–20 mm), with a fine content of <80 μm equal to, or less than 7%, and degrees of saturation near or below 60%. He concluded that the water drawn to the freezing front during the frost heave test must be considered in the evaluation of the material's frost susceptibility. The water drawn and the rate of cooling effect can be expressed using a modified segregation potential, SP_w. He suggested that the normalized SP method might be applicable for the determination of the SP_0 of a granular base course material.

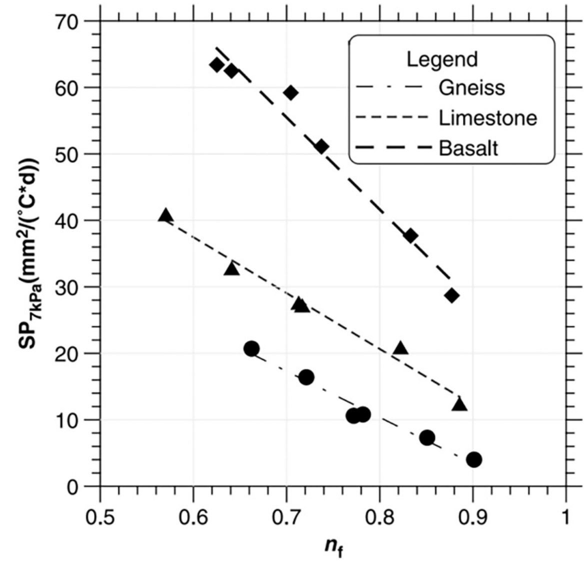

Fig. 5. Segregation potential of 3 different type of crushed rock aggregates at 7 kPa of overburden pressure according to the fine fraction porosity (%) (Bilodeau et al., 2008).

Bilodeau (2009) tested the 0–5 mm portion of 0–20 mm crushed rock aggregates with 6 different shapes of particles size distribution curve. He showed that there is a relationship between the fine fraction porosity (n_f) and the SP for crushed rock granular materials. He showed that the n_f was in relation with the water flow tortuosity in pore channels, as stated by Konrad (1999) and thoroughly described by Côté and Konrad (2003) with Eq. (4).

$$n_f = n/\left(n + (1-n)\bullet fine\%\right) = (n_c - fine\%)/\left(n_c(1-fine\%)\right) \tag{4}$$

where n_f is the fine fraction porosity (< 80 μm), n is the porosity, n_c is the coarse fraction porosity (>80 μm) and *fine%* is the fine content (< 80 μm). A relationship between the fine fraction porosity and SP at 7 kPa of overburden pressure (SP_{7kPa}) was established for 3 different rock types (Fig. 5).

He concluded that a lower fine fraction porosity will lead to higher tortuosity of the flow channels to the freezing front for materials with a

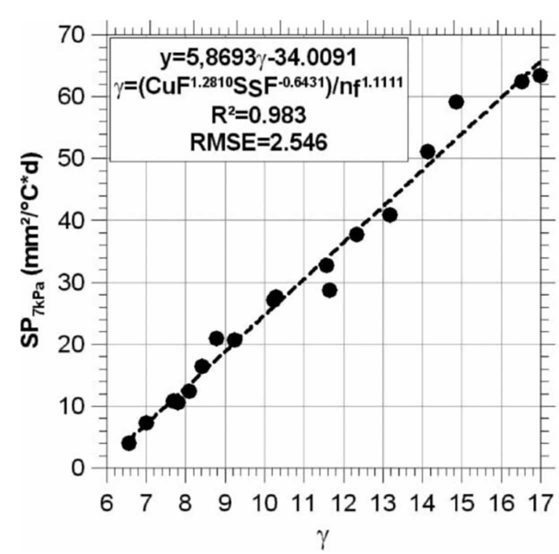

Fig. 6. Relationship between SP_{7kPa} and complex variable ϒ (Bilodeau et al., 2008).

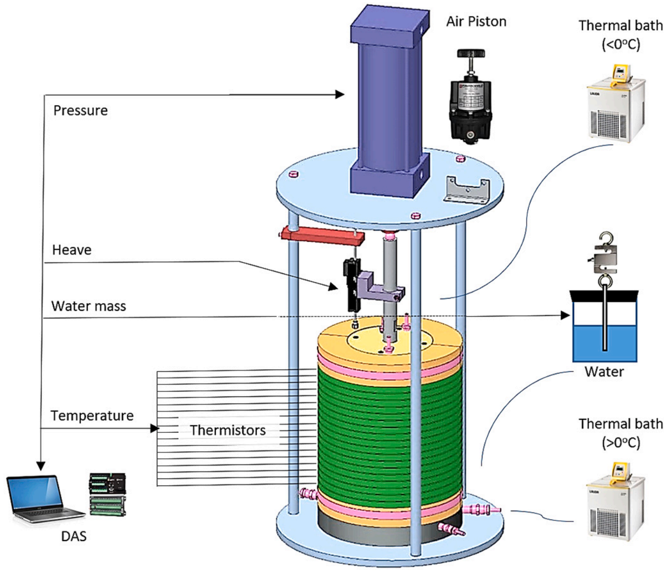

Fig. 7. Multi-rings frost heave cell at NTNU.

relatively low fine content. He also developed a relationship with the specific surface area (Ss) because of its effect on unfrozen water content, dimension, and tortuosity of water channels. The frost susceptibility of CRA will increase with increasing Ss even at relatively low fine content. When Ss reached a certain magnitude, the increase of adsorbed water on fine grains has the effect of reducing water channel dimensions (and increase tortuosity), resulting in a diminution of frost susceptibility, as demonstrated by Konrad (2005).

He developed a relationship by considering the fine content, the uniformity coefficient and specific surface area. The relation is presented in Eq. (5).

$$\gamma = C_u F^x \times S_s F^y \times n_f^z \quad (5)$$

where γ is a complex variable, C_u is the uniformity coefficient, F is the fine content (%) and n_f, the fine fraction porosity. The terms x, y and z are regression coefficients. The $C_u F$ relation expresses the influence of fine particles size distribution and $S_s F$ expresses the influence of fine's mineral content, or rock type. A relationship was built for gneiss, basalt, and limestone crushed rocks, and is presented in Fig. 6.

Xiaoyong et al. (2018) explored the effect of compaction on a natural coarse gravel material. They describe the effect of the degree of compaction on frost heave ratio. Frost heave ratio is the ratio of the heave height on the frozen length of a sample, or a layer, at a given time. The results show that frost heave ratio increased between 85% to 95% compaction and decreased from 95% to 100% compaction.

There is a gap of knowledge concerning the application of the normalized SP concept for crushed rock aggregates. There are few studies on the frost susceptibility of crushed rock aggregates. Konrad (2005), Konrad and Lemieux (2005) and Konrad (2008) did not compare specifically the SP_0 measured in laboratory with the SP_0 estimated from the normalized SP concept. The following sections therefore investigate the normalized SP concept for 23 frost heave tests performed on various rock types. The validation of such a method would be a valuable tool for design optimization.

3. Methodology

Loranger et al. (2019) determined experimentally the segregation potential (SP) of eight, 0–4 mm crushed rock aggregates (CRA). No reliable relationships were found between the SP and the fine content fraction of <80, <63 or < 20 μm. It was concluded that it was not possible to estimate satisfactory the SP from the particle size distribution

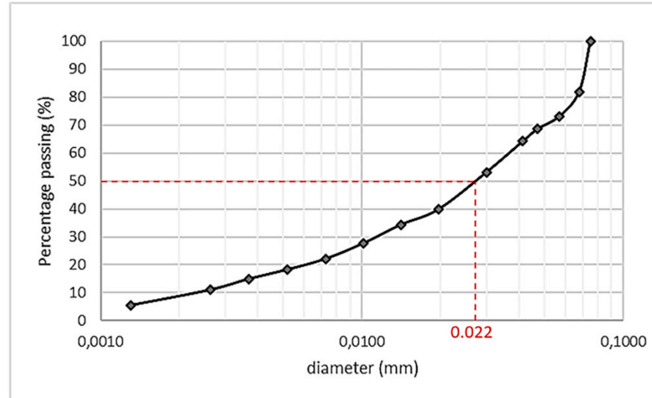

Fig. 8. Determining the $d50_{ff}$ from particle size distribution of <75 μm, here equal to ≈ 22 μm.

of CRA. Also, no usable relationship was found between the SP and mineral content, as proposed by the Austrian mineral criterion. All these reasons motivated the search for a different approach to estimate the SPs of CRA using soils index properties.

Fifteen additional frost heave tests were then performed with variation in rock types, crushing and fine particle size distributions. Details on tested materials are presented at the beginning of the results section. A multi-rings frost heave cell using a step-freezing procedure was used for the experimental program (Fig. 7). The 200 mm high x 150 mm diameter samples were frozen from top, with temperatures at the top and the bottom plates aiming -4 °C and + 2 °C respectively, with water supplied by a Mariotte's bottle to ensure water intake is only driven by a cryosuction process. Thermistors (18), heaving and water mass were recorded by a data acquisition system for 96 h of freezing. No overburden was applied. The detailed procedure and equipment for the frost heave test and SP determination using a multi-rings cell was fully described Loranger et al. (2019).

The normalized SP, noted SP_0/ $SP_{0\ ref}$, is in relationship to the normalized specific surface area (Ss), noted Ss/Ss_{ref} (Konrad, 2005). The normalized SP has a linear relationship with Ss/Ss_{ref} when frost heave is driven by non-clay fines ($Ss/Ss_{ref} < 1$). The next section describes the research procedure to assess the evaluation of SP_0 using the normalized SP ($SP_{0.n}$) and compare it to the SP_0 measured in laboratory condition ($SP_{0\ lab}$).

3.1. The normalized SP

The input parameters are presented, followed by the set of equations needed to process the normalized SP. All equations were modified from Konrad (2005).

The normalized SP – input parameters: soils index properties.

The required soil index properties are the i) mean grain size of the fine fraction ($d50_{ff}$), ii) initial water content (w), iii) liquidity limit (w_L) and iv) specific surface area of the fine fraction (Ss).

i) The mean grain size of the fine fraction <75 μm ($d50_{ff}$) is produced using the hydrometer method (ASTM D7928). The result is expressed in μm when calculating $SP_{0\ ref}$ and Ss_{ref} using the normalized SP equations. Fig. 8 shows an example for finding $d50_{ff}$.

ii) The water content (w) is the water content prior to freezing. However, for CRA, it was calculated from compaction and saturation phases prior to freezing, and cryosuction phases during the freezing.

iii) The liquid limit (w_L) was determined using the falling cone method, as described in the Norwegian NS-8002 standard. Liquid limit was determined for the <75 μm fraction.

iv) Ss: the specific surface area. The Ss was determined on the <75 μm fraction using the methylene blue drop test (ASTM C837) and calculated following the Eq. (6) from Santamarina et al. (2002).

$$Ss = \frac{M_{MB}}{M_{mol\ MB}} A_v\, A_{MB} \frac{1}{m_{soil}} \tag{6}$$

where Ss is the specific surface area (m^2/g). M_{MB} is the mass of methylene blue necessary to saturate the soil/water solution, which is equal to the concentration of the solution (g/ml) multiplied by the amount of solution used in the test (ml) and therefore expressed in grams (g). $M_{mol\ MB}$ is the molar mass of the methylene blue $C_{16}H_{18}ClN_3S$, equal to 319.87 g/mol. A_v is the Avogadro number ($6.02 \bullet 10^{23}$/mol), A_{MB} is the area covered by 1 methylene blue molecule, equal to 130 $Å^2$ ($130 \bullet 10^{-20}$ m^2), and m_{soil} is the mass of dry soil used in the test. According to Konrad (1999), the Ss of the <75 μm (noted only Ss) can be estimated from the <425 μm fraction using Eq. (7).

$$Ss = Ss\ (<425\ \mu m) \times \left(\%fraction < 425\ \mu m / \%fraction < 75\ \mu m \right) \tag{7}$$

Konrad and Valencia Gabezas (2008) confirmed the validity of this method for crushed/partially crushed rock aggregates, and found a linear relationship when testing <400, < 160 and < 80 μm fractions. It is therefore assumed that Ss can be estimated using Ss results obtained from a coarser fraction. According to tested CRA samples from Konrad (2005), Ss ranged from 2.6 to 7.5 m^2/g except for the basalt fines that showed a Ss of 12.6 m^2/g. Kaolinite clay used by Konrad and Lemieux (2005) presents, in comparison, a specific surface of 24.25 m^2/g.

3.2. The normalized SP – equations

The specific surface area of reference (Ss_{ref}) and the segregation potential of reference ($SP_{0\ ref}$) must be determined first. After, the laboratory Ss, w and w_L values are used to choose which equation will be designated to calculate the SP from the normalized SP equations, noted $SP_{0.n}$. The steps involved are:

a) Determine the reference values for Ss_{ref} and $SP_{0\ ref}$. The $d50_{ff}$ determine which of Eq. (8) or Eq. (9) to use. The $d50_{ff}$ is expressed in μm in the equations. The Ss_{ref} is in m^2/g and the $SP_{0\ ref}$ is in $mm^2/{}^oC \bullet d$

When $d50_{ff} < 1\ \mu m$ (8)

$$Ss_{ref} = 25.95 \text{ and } SP_{0\ ref} = 489$$

When $d50_{ff} > 1\ \mu m$ (9)

$$Ss_{ref} = 25.95 - 11.78\ log\ (d50_{ff}) \text{ and } SP_{0\ ref} = 489 - 232\ log\ (d50_{ff})$$

b) The second and last step consists of calculating the $SP_{0.n}$. The set of equation to choose will depend on relation between the Ss of material and the Ss of reference (Ss/Ss_{ref}), and on the water content to liquid limit ratio (w/w_L). Laboratory Ss, w and w_L are required to determine which equation to use. All Ss are expressed in m^2/g and SP in $mm^2/{}^oC \bullet d$.

- If $Ss/\ Ss_{ref} < 1$ (non-clay mineralogy dominance in frost heave behaviour)

$$for\ w \Big/ wL = 0.7 \pm 0.1 \rightarrow SP_{0.n} = SP_{0\ ref} \bullet Ss / Ss_{ref} \tag{10}$$

Table 4
Laboratory segregation potentials $SP_{0\ lab}$.

Quarry	Rock type	Grading (mm)	$d50_{ff}$ (μm)	w_L	Ss (m^2/g)	$SP_{0\ lab}$ ($mm^2/{}^\circ C \bullet d$)
PEB #1	Granite	0–20	20*	28*	2.2	71
PEB #2	Granite	0–20	20*	28*	2.0	54
PEB #3	Granite	0–20	20*	28*	2.3	80
Drapeau #1	Granite	0–0.315	40.0	28*	7.6	165
Drapeau #2	Granite	0–0.08	27.5	28*	6.5	156
Aplitt	Granodiorite	0–4	20.4	29.5	5.1	149
Hadeland	Porphyr	0–4	16.6	29.8	5.2	176
Hellvik	Anortosite	0–4	19.8	30.8	6.8	197
Legruvbakken	Slate	0–4	26.0	37.2	1.5	60
Vassfjell	Gabbro	0–4	18.0	29.7	3.6	111
Lørenskog 1st stage #1	Gneiss	0–4	21.7	29.7	12.6	254
Lørenskog Cone #1	Gneiss	0–4	23.5	31.0	6.7	171
Lørenskog VSI #1	Gneiss	0–4	29.9	28.5	3.7	105
Lørenskog 1st stage #2	Gneiss	0–4	28.3	29.7	12.6	176
Lørenskog Cone #2	Gneiss	0–4	29.8	31.0	5.4	142
Lørenskog VSI #2	Gneiss	0–4	34.8	28.5	4.5	140
Vassfjell Blast	Gabbro	0–4	20.0	28.4	12.4	198
Vassfjell subbus	Gabbro	0–4	17.4	29.7	12.7	189
Vassfjell last stage	Gabbro	0–4	25.0	27.3	7.3	176
Lør. VSI & Velde Coarse	Gneiss/ Granite	0–4	25.0	28*	5.2	134
Lør. VSI & Velde Inter.	Gneiss/ Granite	0–4	28.0	27.8	4.9	130
Lør. VSI & Velde Fine	Gneiss/ Granite	0–4	22.0	29.4	4.7	136
Lør. VSI & Lør. VSI	Gneiss/ Granite	0–4	29.9	28.5	6.3	162
*: estimated values						

$$for\ w \Big/ wL > 0.8 \rightarrow SP_{0.n} = SP_{0\ ref} \bullet \left(0.08 + 1.42 \left(Ss / Ss_{ref} \right) \right) \tag{11}$$

- If $Ss/\ Ss_{ref} > 1$ (clay mineralogy dominance in frost heave behaviour)

$$for\ w \Big/ wL = 0.7 \pm 0.1 \rightarrow SP_{0.n} = SP_{0\ ref} \bullet \left(Ss / Ss_{ref} \right)^{-0.85} \tag{12}$$

$$for\ w \Big/ wL > 0.8 \rightarrow SP_{0.n} = SP_{0\ ref} \bullet 1.5 \left(Ss / Ss_{ref} \right)^{-0.55} \tag{13}$$

All crushed rock aggregates were processed using this methodology to compare the normalized SP ($SP_{0.n}$ with the laboratory SP ($SP_{0\ lab}$).

4. Results

This section presents the results from the soil index parameters investigation, laboratory SPs, and the normalized SPs. The CRA are from different quarries in Norway: Aplitt, Hadeland, Hellvik, Legruvbakken, Vassfjell, Lørenskog and Velde, and Canada: PEB and Drapeau. The 0–4 mm fraction was mainly tested and was either sieved down from a coarser fraction or was originally a final product. The Lørenskog and Vassfjell CRA were tested at different steps of the crushing process in their respective quarry. For Lørenskog, this included CRA from the first

Table 5
Normalized segregation potential $SP_{0.n}$.

Quarry	d50ff (μm)	Ss_{ref} (μm)	$SP_{0\ ref}$ (mm^2/°C•d)	Ss (m^2/g)	Ss/Ss ref	$SP_{0.n}$ (mm^2/°C•d)
PEB #1	20*	10.6	187	2.2	0.20	69
PEB #2	20*	10.6	187	2.0	0.18	64
PEB #3	20*	10.6	187	2.3	0.22	73
Drapeau #1	40.0	7.1	117	7.6	1.07	169
Drapeau #2	27.5	9.0	155	6.5	0.72	172
Aplitt	20.4	10.5	185	5.1	0.48	143
Hadeland	16.6	11.6	206	5.2	0.43	141
Hellvik	19.8	10.7	188	6.8	0.63	185
Legruvbakken	26.0	9.3	161	1.5	0.16	50
Vassfjell	18.0	11.2	198	3.6	0.32	105
Lørenskog 1st stage #1	21.7	10.2	179	12.6	1.23	240
Lørenskog Cone #1	23.5	9.8	171	6.7	0.68	180
Lørenskog VSI #1	29.9	8.6	147	3.7	0.43	102
Lørenskog 1st stage #2	28.3	8.8	152	12.6	1.42	188
Lørenskog Cone #2	29.8	8.6	147	5.4	0.63	143
Lørenskog VSI #2	34.8	7.8	131	4.5	0.58	118
Vassfjell Blast	20.0	9.5	165	12.4	0.77	194
Vassfjell subbus	17.4	11.3	201	12.7	1.11	183
Vassfjell last stage	25.0	10.6	187	7.3	1.16	165
Lør. VSI & Velde Coarse	25.0	9.5	165	5.2	0.55	141
Lør. VSI & Velde Inter.	28.0	8.9	153	4.9	0.55	132
Lør. VSI & Velde Fine	22.0	10.1	178	4.7	0.46	131
Lør. VSI & Lør. VSI	29.9	8.6	147	6.3	0.73	164
*: estimated values						

step of crushing, the cone crushing (3rd step) and the VSI crushing phase (4th step). The Vassfjell tests included a 0–4 mm fraction from blasted materials, subbus (which is a mix of 1st,2nd and 3rd crushing phase) and the 3rd crushing phase (cone crusher). Three fillers produced with an air classifier from the Velde quarry (coarse, intermediate, and fine) were used in a series of tests including the VSI Lørenskog aggregates for coarser fraction (0.125–4 mm) and Velde for the finer fraction (0–0.125 mm).

Table 4 presents the 23 results of $SP_{0\ lab}$, with their associated soil index parameters.

All tests were proceeded after, using the normalized SP method. The ratio w/w_L was determined to be >0.8 for all CRA using the water flow back mass at the end of the frost heave test, but for Vassfjell. Calculation details for determining the $SP_{0.n}$ are presented in Table 5.

For the Aplitt quarry per example, we first determined Ss_{ref} and $SP_{0\ ref}$ using the $d50_{ff}$ in Eq. (9), as $d50_{ff}$ was >1 μm. Then we determined that $w/w_L > 0.8$. Eq. (11) was then used to calculate $SP_{0.n}$ because $Ss/Ss_{ref} < 1$.

The comparison of results from $SP_{0\ lab}$ and $SP_{0.n}$ is presented in Fig. 9. Dotted lines refer to a ± 15% variation from the line of equality.

5. Discussion

This section first compare laboratory and normalized segregation potentials. The initial water content to consider in the normalized SP for CRA is after discussed. An analyse of the specific surface area variability is then presented, and finally, a relation is proposed to estimate the SP of CRA according to the Ss, when the Ss < 8 m^2/g.

5.1. Comparison between $SP_{0\ lab}$ and $SP_{0.n}$

Fig. 11 presents the $SP_{0\ lab}$ versus the $SP_{0.n}$ for all CRA in this study. Results show a good correlation between $SP_{0\ lab}$ and $SP_{0.n}$, with a coefficient of determination (R^2) of 0.95. This validates the normalized SP methodology for determining the $SP_{0.n}$ of CRA. A method that uses common index parameters to estimate the frost susceptibility of CRA is

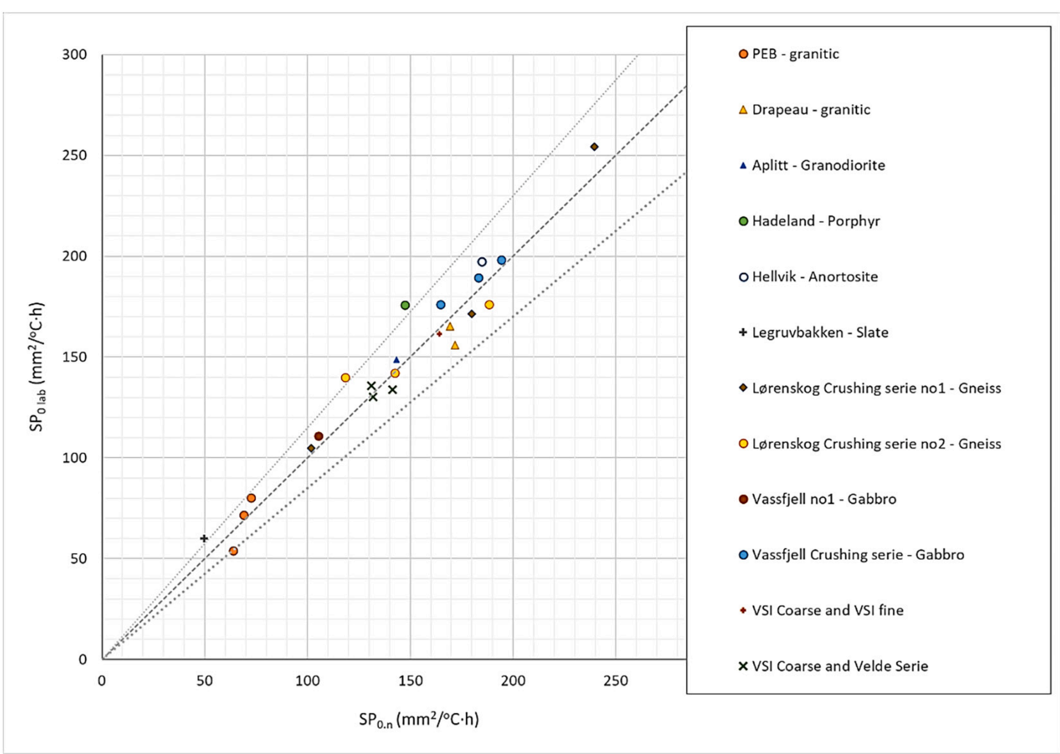

Fig. 9. Laboratory segregation potential, $SP_{0\ lab}$ vs. $SP_{0.n}$ calculated from normalized SP.

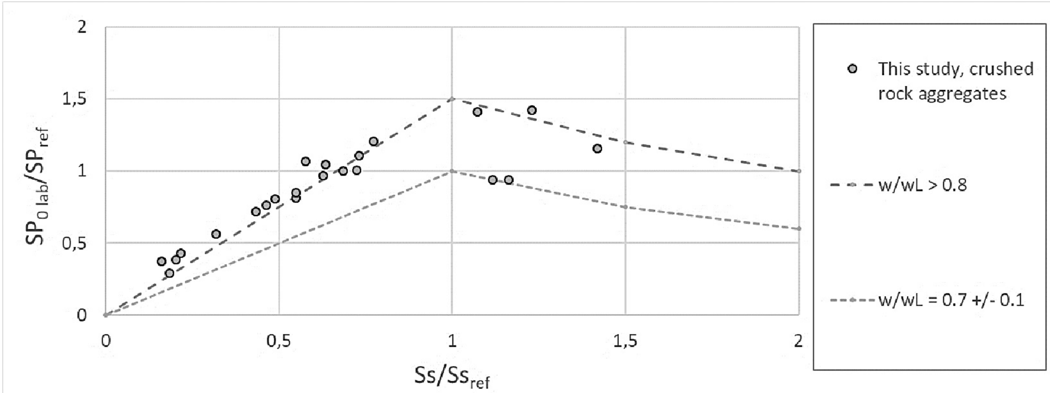

Fig. 10. Normalized SP as a function of normalized Ss as presented by Konrad (2005).

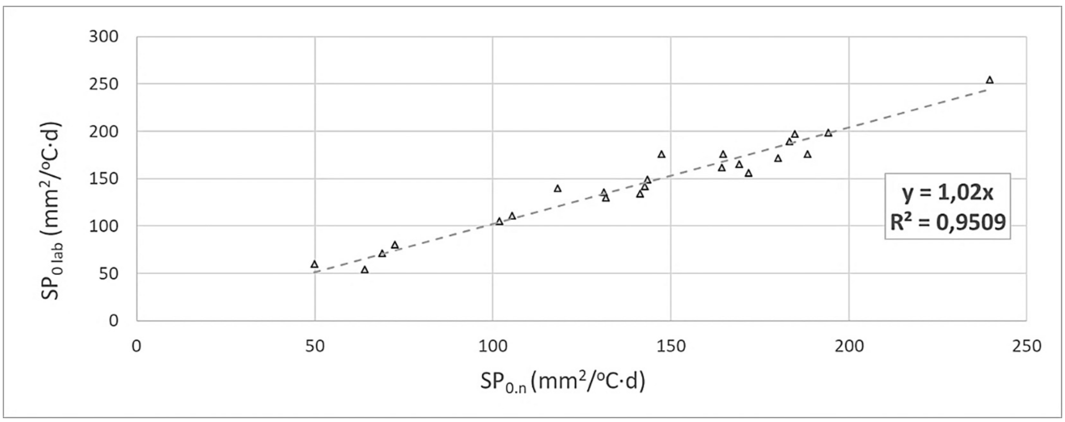

Fig. 11. Relation between $SP_{0\ lab}$ and $SP_{0.n}$ for Norwegian crushed rock aggregates.

interesting from a cost-effective point of view. E.g., it can permit low budget project to use such relation and make optimization design using a model as the SSR model (Saarelainen, 1992).

5.2. Initial water content

The normalized SP described in Konrad, 2005 used the CRA fine fraction <80 µm. The CRA were added as a slurry before being consolidated and tested. Water content was determined before the frost heave test started. In this study, however, the samples were molded at w ≈ 0.07 before being transferred to the cell for the conditioning phase. The samples were saturated, and then drained some time before starting the test. It was observed that there was more water input than ice formation contribution when comparing the water mass with the heaving. Also, it was observed at the end of the test that there was a water flow back to the water bottle that was not caused by ice melting, but only by water drainage when stopping the thermal bath (rapid flow back). This phenomenon was also observed by Konrad (2008) and Uthus (2007). Then, the relationship of w/w_L for the CRA tends to be between 0.85 and 1.0, as the unfrozen portion gets almost fully saturated because of the cryosuction process. Results were plotted as $SP_0/SP_{0\ ref}$ according to Ss/Ss_{ref} (Fig. 10) as done by Konrad, 2005 (Fig. 4, literature review section). 18/23 tests of 0–4 mm CRA from this study followed the same 'non-clay driven' behaviour than the CRA of Konrad (2005). The CRA with a SS/Ssref >1, i.e. 5/23 tests, were Vassfjell ($w/w_L = 0.7 \pm 0.1$ relationship) and 4 early stage crushing aggregates. Those aggregates experienced a frost susceptibility behaviour borderline between 'non-clay driven' and 'clay driven'. Further investigation, e.g., on mineral content, would be necessary to address why those aggregates did not behave as the others.

5.3. Specific surface area variation

According to Rieke (1983), a relationship exists between the specific surface area (Ss) of the <75 µm fraction and the SP of sand, silt, and clay. In this study, relationship between the Ss and $SP_{0\ lab}$ of all CRA was judge unsatisfactory ($R^2 = 0.78$). The Ss (< 75 µm) from this study are comparable with Konrad (2005) results, showing Ss values of <8 m^2/g (but for one basalt in Konrad (2005) with a Ss ≈ 12.5 m^2/g). The CRA from an early stage of crushing also presented Ss values of ≈ 12.5 m^2/g and a poor relation to the normalized SP, and it was investigated furthermore.

In more detail, two gneiss (Lørenskog) and one gabbro (Vassfjell) series were tested at different crushing stages. For Lørenskog, a 1st stage crushing, a cone crushing (3rd stage crushing) and a VSI crushing (4th stage crushing) from 2 different year of production were analyzed. The Ss for the 1st stage, cone and VSI crushing, were 12.6, 6.7 and 3.7 m^2/g respectively for the first series, and 12.6, 5.4 and 4.5 m^2/g respectively for the second series. For Vassfjell, a blast subbus and 3rd crushing stage were analyzed, with Ss of 12.4, 12.7 and 7.3 m^2/g respectively. The Ss variabilities were believed to be caused by either grain-surface condition or mineral content, or a combination of both.

Konrad and Valencia Gabezas (2008) show that the grain-surface condition was affecting the methylene blue test results for weathered till fine fractions. The test is based on the principle of a monolayer of molecules on the surface of a grain. The methylene blue can fill small cracks and asperities when the grain surface is irregular, leading to an overestimation of the adsorbed methylene blue solution and consequently, of the Ss (Fig. 12).

Blasting is known to produce micro-cracking in rocks. As rocks go

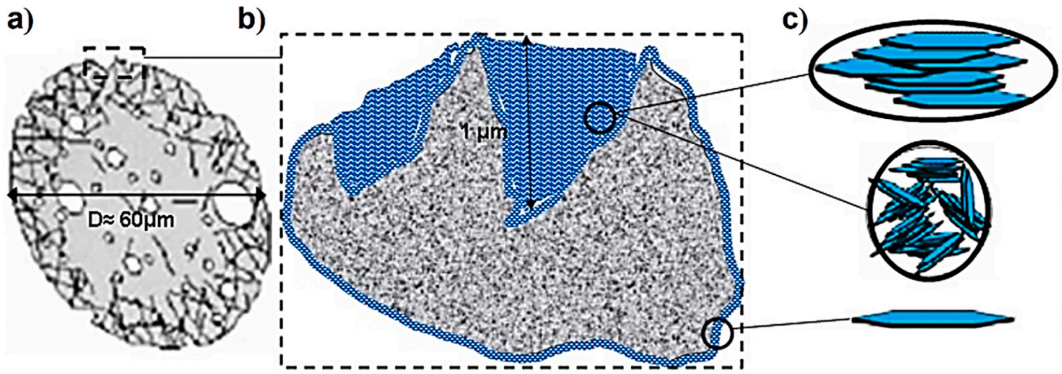

Fig. 12. a) Grain surface alteration. b) Methylene blue molecules in asperities. c) Methylene blue molecules possible arrangement (Konrad and Valencia Gabezas, 2008). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

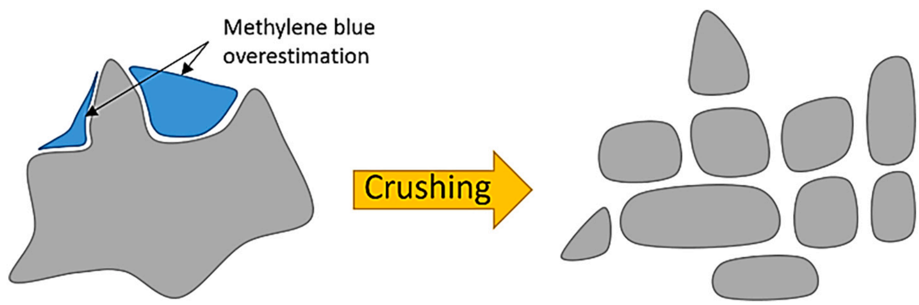

Fig. 13. Overestimation of methylene blue on poorly crushed and well crushed fine particle. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

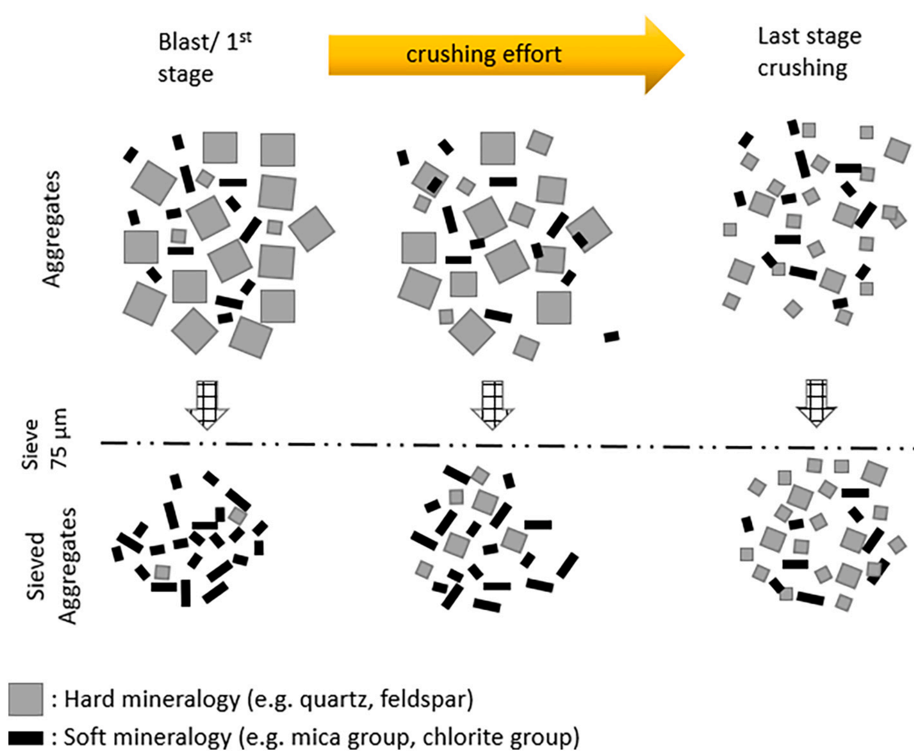

Fig. 14. Mineralogy enrichment concept according to crushing phase.

through crushing phases, the percentage of damaged particles will decrease (Fig. 13). Note that a methodology for correcting overestimation of methylene on weathered till particles has been proposed by Konrad and Valencia Gabezas (2008).

Softer mineral content (e.g., mica and chlorite) can be easily grinded to finer particle sizes at an early crushing stage, leading to a soft mineral

Table 6
Partial mineral variation of 3 gneiss according to different analysis (modified from Uthus, 2007).

Mineralogy	Cubical gneiss				Flaky gneiss				Swedish gneiss			
	%Q	%P	%F	%M	%Q	%P	%F	%M	%Q	%P	%F	%M
Thin section	47	44*		0	40	50*		8	19	37*		33
XRD < 63 um	12	46	24	14	16	23	18	36	8	34	18	35
XRD < 20 um	27	31	31	6	21	37	16	17	21	53	11	11

Q: quartz; P: plagioclase; F: Alkali feldspar; M: mica
*: thin section measured feldspar content (plagioclase and alkali feldspar) together

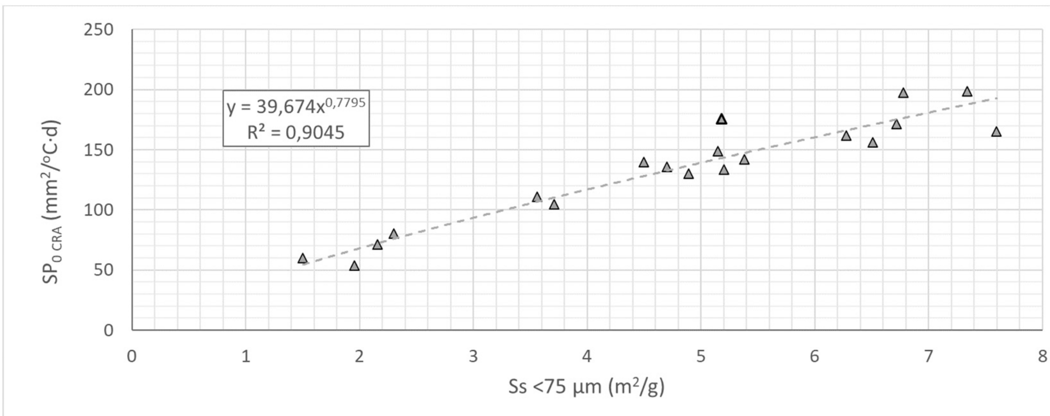

Fig. 15. Relation between $SP_{0\ lab}$ and specific surface area of <75 μm fraction, Ss, for Norwegian crushed rock aggregates.

enrichment in the fine fraction. At subsequent crushing phases, harder type of minerals turns to finer fractions, therefore reducing this effect (Fig. 14).

The mineral enrichment in the fine fraction was observed by Uthus (2007), who compared thin sections with X-ray diffraction (XRD) of <63 and < 20 μm fractions for 3 gneiss: a cubical gneiss (fine grained), a flaky gneiss (foliation, very fine to fine grained) from Norway, and a gneiss from Sweden (fine to medium grained). It was showed that a mica enrichment was important in the <63 μm fraction grain size interval for the Norwegian rocks when compared to the thin layers. This effect seemed less perceptible on the Swedish aggregate that had a coarser crystallography. Micas are, according to Prestvik (1992, cited by Uthus, 2007), softer minerals with weaker chemical bonds that can lead to relative accumulation in the fines when crushed. Table 6 summarizes these results.

Results, clearly show a reduction of Ss as crushing phase numbers increase but the exact cause would have to be investigated furthermore.

5.4. Segregation potential of crushed rock aggregates vs the specific surface area

The CRA with a Ss of <8 m^2/g, from last stage crushing, were used to develop an equation as it was showing an excellent correlation, with a coefficient of determination $R^2 = 0.9045$ between the $SP_{0\ lab}$ and the Ss of <75 μm fraction, as shown in Fig. 15. Note that Konrad (2005) also analyzed differently the basalt (Ss = 12.6 m^2/g) than his other CRA with Ss of 2.6 to 7.5 m^2/g (Fig. 4).

The function of $SP_{0\ lab}$ according to the Ss <75 μm fraction is presented in Eq. (14). As the $SP_{0\ lab}$ was showed to be in accordance with the $SP_{0.n}$, it was judged adequate to generalize Eq. (14) as $SP_{0\ lab} = SP_{0.n} = SP_{0\ CRA}$, or SP_0 for crushed rock aggregates with Ss < 8 m^2/g for the <75 μm fraction.

$$SP_{0\ CRA} = 39.674\ Ss_{<75\ \mu m}^{0.7795} \tag{14}$$

This equation only needs the determination of the Ss (<75 μm fraction) to be processed, reducing time and effort in estimating the SP of a CRA.

6. Conclusion

A comprehensive laboratory study was performed to evaluate the use of soil index properties to satisfactorily estimate the segregation potentials of crushed rock aggregates. The goal was ultimately to develop a better understanding of the frost susceptibility of crushed rock aggregate and its assessment in frost design models. It is expected than substantial economical and environmental benefits can result from the optimization of pavement design for frost action. The segregation potentials measured in laboratory conditions were precise and relevant.

The methodology proposed by Konrad (2005) was proven to be applicable to crushed rock aggregates. The comparison between the segregation potential obtained from soil index properties applied to the normalized segregation potential equations ($SP_{0.n}$) and the segregation potential obtained from laboratory experiments ($SP_{0\ lab}$) gave a coefficient of correlation (R^2) equal to 0.95.

The relation between $SP_{0\ lab}$ and the specific surface (Ss) area of the fine fraction (<75 μm) was also examined. It was found that an excellent correlation ($R^2 = 0.9045$) links the Ss to $SP_{0\ lab}$, and therefore $SP_{0.n}$, for CRA with a Ss of <8 m^2/g, calculated on the fine fraction (<75 μm), (referred in Eq. (14)).

It was found that all CRA with high Ss values (> 12 m^2/g in this study) were from early stage crushing production. It is known that the Ss can be overestimate due to methylene blue molecule filling altered surfaces of the particles instead of covering only its surface by a mono layer (Konrad and Valencia Gabezas, 2008). Also, soft/ weak mineral enrichment (e.g., mica) at early crushing stage (observed by Uthus, 2007) will contribute to the overestimation of Ss. Further research on this subject would permit to measure their effects on the Ss evaluation.

This study therefore confirms that the normalized segregation potential equations were applicable to crushed rock aggregates. This study also showed that it is possible to estimate accurately the $SP_{0\ lab}$ with just the specific surface area of the fine fraction (<75 μm) of crushed rock when <8 m^2/g (Eq. (14)). The relationship should be validated further as it have the advantage of using only the Ss measured in laboratory condition and have the potential to significantly help in frost design at lower cost.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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