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Effect of surface roughness and chemistry on ice bonding to asphalt aggregates

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ABSTRACT

In winter maintenance, it is common to use chemicals to weaken the bonding between snow and a road. However, this practice damages the road pavement and has a negative impact on the environment. Moreover, aggregates are the main component of asphalt mixtures and, due to the wear of traffic, typically make up the surface of roads. For this reason, with the aim of reducing the need for chemicals, it is interesting to study how stone aggregates interact with ice and snow and try to evaluate if it is possible to find a type of stone which forms weak bonds with ice and snow.

For the study, two rocks with different chemical compositions commonly used as aggregates on roads, granite and gabbro were selected. Rock–ice interactions were studied using an experimental setup that measured the bonding force between an ice sample and a rock substrate. Ice bonding data were analysed with respect to the type of rock and the effect of the rock surface. The results showed that the bond failure between the ice and rock was adhesive in nature, and ice bonding increases when the surface roughness increases, regardless of the chemical composition of the stone.

1. Introduction

Road surface conditions affect traffic safety, mobility and transport efficiency. Slippery road conditions due to ice and snow cause many accidents around the world (Andersson and Chapman, 2011; Andreescu and Frost, 1998; Chapman and Thornes, 2011; Norman et al., 2000; Riehm et al., 2012; Usman et al., 2011). In countries with intense snowfalls during the winter season, the mechanical removal of snow from roads is a necessary and common activity. Snow falling on roads rapidly bonds to the pavement and forms a compacted crust that is difficult to remove and that may become slippery at temperatures near melting. To avoid this, chemicals are often spread to break the bond to the pavement and to keep the snow ploughable until it can be removed by highway maintenance personnel (Minsk, 1998).

However, it is well known that these chemical products, especially chlorides, can have a negative impact on the environment close to the road (D'Itri, 1992; Fay and Shi, 2012; Ramakrishna and Viraraghavan, 2005; Ratkevičius et al., 2014). In addition, they may contribute to the deterioration and deformation of pavements and road side structures (Dore et al., 1997; Hassan et al., 2002; Özgan et al., 2013; Shi, 2005; Shi et al., 2009) and they can accelerate corrosion of vehicles (Li et al., 2013; Oliver and Sephton, 2003; Xi and Xie, 2002). The severity of these negative impacts can vary between different ecological and climatic regions and always have to be evaluated against the positive impacts such as increased traffic safety and improved/predictable mobility. But regardless of the actual severity, the social awareness of these negative impacts motivate road administrations, agencies and researchers to search for methods that ensure safe road surface conditions while reducing the use of these chemical compounds (e.g. Liu et al., 2014; Sobolev et al., 2013; Giuliani et al., 2012; Shi et al., 2011).

One method to reduce the use of chemicals on roads during snowfalls could be to construct pavements to which snow does not adhere as strongly. With this purpose in mind, it is important to study the bonding of snow to pavements, looking for low adhesion materials that would facilitate snow removal from roads.

As snow is a collection of ice particles, it is important to revisit previous studies of ice adhesion. Most studies on ice adhesion have been performed by freezing water onto different substrates (e.g., Meuler et al., 2010; Dotan et al. (2009), Matsumoto and Daikoku, 2009; Kulinich and Farzaneh, 2009; Murase et al., 1994; Roberts, 1981; Bascom et al., 1969). These studies showed that the chemistry and roughness of a surface are the main factors that affect the adhesion of ice. Sayward (1979) concluded that the geometry and especially the chemistry of the interface are critical for adhesion, and Zou et al. (2011) found that the ice adhesion strength is correlated to the surface chemistry (water affinity) only when the surfaces have similar roughnesses.

On asphalt pavements, ice adhesion has been less studied. Penn and Meyerson (1992) showed that even a very small road surface roughness makes it difficult to completely remove ice from a pavement using

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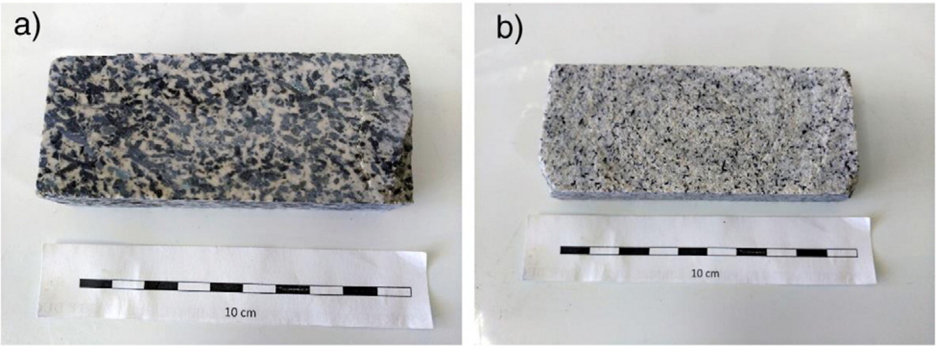

Fig. 1. Images of Vassfjell gabbro (a) and Kuru granite (b) samples used to measure ice bonding.

traditional mechanical methods. Recently, Dan et al. (2014) found that the adhesive strength of ice to asphalt pavements is higher at higher pavement surface roughness values.

The process through which snow bonds to a road is, however, clearly different from water freezing to a road. Snow crystals fall to the pavement, and as traffic pushes them into the road texture, bonds are formed between the crystals and the pavement. Snow bonding is, in other words, more similar to the phenomenon of contact bonding described by Haisma and Spierings (2002). This type of ice contact bonding to surfaces has mostly been studied as comparisons between different chemicals (Cuelho and Harwood, 2012) or types of ice (Nixon and Wei, 2003). The same is true of a study by Adams et al. (1992), although they also found that the bonding strength of compressed snow varies significantly between granite and limestone, two different rocks commonly used as aggregates in roads. No attempt was made to explain this difference, however, and there was no consideration of surface roughness. To better understand the contact bonding of snow/ice to a pavement, an experimental setup that could simulate this process was developed from a previous setup designed to measure the bonding of ice to ice (Wåhlin, 2014). This experiment measured the bonding force between an ice sample, meant to simulate an individual snow grain, and a rock substrate. The choice of a rock substrate instead of an asphalt substrate was made to reduce the spatial variability across the substrate. This idealisation can be defended by the fact that aggregates are the main components of asphalt mixtures and that after a relatively short time of traffic wear, these aggregates constitute a large majority of the road surface (Asi, 2007).

To better understand which factors affect the bonding of snow to a road, we examined how ice contact bonding is affected by the parameters that have proven most important in ice adhesion, namely, the roughness and the chemistry (water affinity) of the surface to which the snow/ice bonds. The long term goal of the study is to provide knowledge that can be used to propose types of rocks for aggregates, resulting in roads that require less chemicals to maintain during snowfalls.

2. Method

2.1. Rock substrates

The rock types selected for this study were gabbro and granite (Fig. 1a and b respectively), two rocks commonly used as aggregates in roads (Hunter, 2000; Smith et al., 2001). The mineralogical composition (Table 1) of gabbro is amphibole, plagioclase, chlorite, epidote, alkali feldspar, quartz and carbonate (Nålsund, 2014), while that of granite is alkali feldspar, quartz, plagioclase and biotite (Nyman, 2007; Selonen et al., 2012).

These two rock types were selected because of their different chemical compositions and similar textures. Granite is considered a hydrophilic rock because of its high content of silica (Bagampadde, 2004; Hicks, 1991; Tarrer and Wagh, 1991; Wasiuddin et al., 2006), which absorbs water through hydrogen bonding to surface hydroxyls $(\mathrm{SiOH}^-)_n \leftrightarrow (\mathrm{H_2O})_n$ (Bagampadde, 2004; Bagampadde et al., 2005; Mazurek et al., 2009). Gabbro has a lower content of silica minerals and should therefore be more hydrophobic than granite. As mentioned in the introduction, the most common hypothesis is that materials having poor chemical affinity with water will also have weak ice adhesion properties (Dotan et al., 2009; Kulinich and Farzaneh, 2004; Petrenko and Peng, 2003; Sayward, 1979). While the rocks have different chemistries, they have a similar crystalline phaneritic texture (Le Bas and Streckeisen, 1991; MacKenzie et al., 1982). This means that they will show a similar response to surface treatments, allowing for a comparison between rocks of different chemical compositions with similar surface roughnesses.

The gabbro rock was cut with a diamond disc to obtain 3 prismatic samples with dimensions of 100 × 40 × 20 mm. Each prismatic sample was treated differently to obtain a different substrate. One sample was polished by hand using a diamond abrasive with a 45 μm particle size to obtain a smooth substrate (GaP). Another sample was treated with a rotating diamond milling cutter mounted on a drilling machine to obtain a rough substrate (GaR). The last sample was left "as received" after the diamond disc cut (GaDD), producing a substrate of intermittent roughness. After the surface treatments, all substrates were cleaned in an ultrasonic bath to remove the diamonds and other particles from the surface. Finally, the rock substrates were dried using a heater until constant weight to remove absorbed water from the rock surfaces. The same procedure was repeated for the granite rocks to obtain corresponding substrates, polished (GrP), roughened (GrR) and "as received" (GrDD). This resulted in a total of six different substrates (Table 2).

2.2. Rock surface characterisation

The surface roughness of the substrates was measured using the optical roughness tester TRACEiT, patented by InnowepGmbH, Würzburg (Germany). It measures the 3D topography of a surface

Table 1
Mineralogy semiquantification of gabbro (Nålsund, 2014) and granite (Nyman, 2007).

Rock type	Mineralogy (%)							
	Quartz	Plagioclase	K Feldspar	Amphibole	Biotite	Epidote	Chlorite	Carbonate
Vassfjell gabbro	1	18	6	41		12	18	4
Kuru granite	40	22	35		3			