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Measurement of fracture toughness of an ice core from Antarctica

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Abstract

The critical fracture toughness is a material parameter describing the resistance of a cracked body to further crack extension. It is an important parameter to simulate and predict the break-up behaviour of ice shelves from calving of single icebergs to the disintegration of entire ice shelves over a wide range of length scales. The fracture toughness values are calculated with equations that are derived from an elastic stress analysis. Additionally, an X-ray computer tomography (CT scanner) was used to identify the density as a function of depth. The critical fracture toughness of 91 Antarctic inland ice samples with densities between 840 to 870 $\mathrm{kg\,m^{-3}}$ has been determined by applying a four-point-bending technique on single edge v-notched beam samples. The examined ice core was drilled 70 m north of Kohnen Station, Dronnning Maud Land (75°00′ S, 00°04′ E, 2882 m). Supplementary data are available at doi:10.1594/PANGAEA.835321.

1 Introduction

In order to simulate and predict calving of icebergs or the disintegration and break-up of ice shelves, the deformation and stress states within ice shelves need to be identified and related to material properties. Both, deformation and stress states vary with the position in an ice shelf. Therefore, the knowledge of material data is crucial for numerical simulations. Depending on the time scale under consideration one has to distinguish the material response of ice as viscous or elastic. On the long term ice reacts like a viscous fluid. Frequently, a material model according to Glen is used, where the important parameters are the shear viscosity and stress exponent, see Glen (1958) and Greve and Blatter (2009). On the other hand, the elastic response is valid on short time scales and the relevant parameters are fracture and rupture. Classically, the polar ice is assumed to be isotropic and therefore requires the knowledge of Young's modulus and Poisson's ratio. With the awareness of these model parameters simulations can be performed. Additionally, measured velocity fields can be used to compute the strain and stress state locally.

In the presence of cracks, the stress field is singular at the crack tip for linear elastic materials, thus stress based criteria fail to predict crack growth. However, the asymptotic behaviour is given by the stress intensity factors (SIFs), usually denoted by K_{I}, K_{II} or K_{III}. For details on fracture mechanical concepts and the different fracture modes, see Gross and Seelig (2011). The SIF depends on the loading, the elastic material properties and the boundary conditions (geometry) under consideration. Once the SIF is known it is compared to a critical fracture toughness value K_{Ic}, where we restrict attention to Mode I crack scenarios, as they typically represent the worst-case loading condition. For ice the fracture toughness is influenced by many factors, such as density, grain size, temperature, microstructure, water content, salt content and so on. Thus, it is experientially challenging to measure fracture toughness. There exist different techniques to measure the Mode I fracture toughness of a material such as three- and four-point loaded beams with a notch, for example see Goodman and Tabor (1978), Timco and Frederking (1982), Wei et al. (1991), Weber and Nixon (1996a) and Weber and Nixon (1996b) for sea water and fresh water ice. Furthermore, different parameters, which have an influence on the critical fracture toughness are analysed in Nixon and Schulson (1987), Nixon (1988) and Nixon and Schulson (1988) for tensile bars with a circulatory notch. Previous investigations on fracture toughness of marine and glacier ice are found in Rist et al. (1999) and Schulson and Duval (2009). Their results are used as reference values in the present investigation, where ice of an ice core from Antarctica, denoted as B34, was examined. This core was drilled at Kohnen station on the East Antarctic plateau, a site of low accumulation rates and temperatures. Figure 1 shows a map of this region.

The mechanical testing was performed in the ice lab at the Alfred-Wegener-Institute in Bremerhaven. The experimental setup was designed and built at the Institute of Material Science at the Technische Universität Darmstadt.

The fracture toughness for ice cores from Antarctica have been to date tested with two experimental setups. Rist et al. (1996) utilized a three-point bend geometry for a chevron-notched round-bar specimen, which was used to perform experiments on Antarctic ice from one ice core. Rist et al. (1999) determined the critical stress intensity factor dependency on the density and porosity also using a short-rod specimen geometry. The results from 18 different core samples were presented, where a controlled crack growth was obtained. The tests cover densities from 560 to 871 $\mathrm{kg\,m^{-3}}$. Rice (2000) had analysed for the case of ceramics, that there do not exist one single and perfect method, so the results of the fracture toughness are only estimates.

2 Experimental methodology

2.1 Sample preparation

Bar shaped samples for fracture testing were obtained from the B34 ice core, originally from a depth between 94.6 m and 96 m. Prior to testing an X-ray computed tomography (CT scanner) was used to determine the density as a function of depth, shown in Fig. 2. During analysis each 1 m long ice core was weighted to estimate the mean density, a parameter used for the CT analysis calibration. The ice core was then cut into 12.6 cm long cylinders. The average density of the middle section of each disc, near the location of the fracture notch, was characterized, shown as red circles in Fig. 2. An accurate position of the notch was determined by taking into account the material loss due to the cutting process and the loss of waste ice. The mean density was calculated as an average considering 2 cm of the surrounding density values.

Antarctic ice from an ice core was chosen, as we intended to have a sample that represents the ice in situations to which the observational data will be applied (e.g. simulations of ice shelf crack evolution) best. Artificially created samples would neither contain the impurities found in nature nor would represent the grain size distribution. As the porosity of the material, and hence the density, is the key parameter that determines the critical fracture toughness, the sample selection was performed by selecting a suitable density range. As the main aim was to increase the estimations of K_{Ic} at specific densities with sufficient statistics, one part of the ice core with nearly constant density was selected to be able to obtain a large amount of samples. This could in future be extended by performing the same experiments with samples of other densities.

Because it was not intended to obtain the fracture toughness over a wide range of density, representative for breaking ice shelf-ice, ice from just below the firn ice transition at a depth of 88 m (Freitag et al., 2013) was used. The accumulation rate at Kohnen Station is 65 mm of water equivalent or ≈ 72 mm of ice. A 12.6 cm long bar contains the accumulation of almost two years. The accumulation on ice shelves is with $> 200\,\mathrm{mm\,a^{-1}}$ and up to more than 500 mm water equivalent generally much higher.

Therefore, during testing of the critical fracture toughness, it was important to minimize the density variation between samples. For this purpose, the core was cut into 9 cylinders with 12 samples each. Each cylinder was a 12.6 cm long section, resulting in samples cut at a 1.4 m depth interval for the B34 ice core. The ice core had a radius of $r = 50\,\mathrm{mm}$. Thus the experiments could be performed with 12 samples with nearly identical mean density. The bar shaped samples were cut with a band saw at −20° C from the B34 ice core. Figure 3 shows a schematic cross section of an ice core with the samples location pattern. The location of the sample in one cross section of the ice core had no identifiable influence on the measured critical fracture toughness. Each specimen had a final thickness $W = 14.30\,\mathrm{mm}$, a width $B = 27.55\,\mathrm{mm}$ and a length $L = 126\,\mathrm{mm}$. Due to the nature of the preparation process the sample thickness and width were found to vary with a standard deviation of 0.16 mm and 0.27 mm, respectively. The minor variations in sample size were not found to influence to fracture toughness measurements. Prior to testing, a notch was milled into each sample with a depth $a \approx 2.5\,\mathrm{mm}$ and a notch radius $r_a \approx 100\,\mathrm{\mu m}$ at −15 °C. Although, it is understood that the notch radius can influence the observed fracture toughness values, depending on the material's grain size, Rist et al. (2002) has found that there is no effect of the grain size on the fracture toughness of granular ice of the Ronne Ice Shelf at different depths.

Fig. 4 shows a representative microstructure of the tested ice. It is apparent that there is a distribution of grain sizes as well as significant porosity, indicated by the dark regions. The grain size was determined along the white line, which extends along the entire length of the sample and represents approximately 90 grains. The measured mean grain size was found to be 1.15 mm, with a minimum and maximum observed grain size of 0.05 and 4.58 mm. The standard deviation was determined to be 0.81 mm along this line. The grain size was not found to vary in other analyzed sample sections, indicating that the states grain size distribution is representative of the entire B34 ice core.

2.2 Fracture toughness measurements

The fracture toughness K_I is a material parameter that is used to characterize a materials resistance to further crack growth of a preexisting flaw, which is important in understanding when a material or structure will fail. Flaws can refer to a crack, grain boundary, pore, or other microstructural defects inherent in imperfect materials. In the case of a linear elastic material, K_I also fully defines the stress fields at the crack tip, which are intensified due to the presence of a sharp crack. If it is assumed that the material fails at a particular stress, then there exists a critical fracture toughness value K_Ic that can be used to predict the level of external mechanical load required to grow a crack of a given length and orientation. There are three fracture modes that define different loading conditions. Mode I, often referred to as the opening mode, is found when the external load is applied perpendicular to the fracture surface. This loading condition occurs often and represents the worst-case scenario due to the relatively low fracture toughness values in comparison to Modes II and III, i.e. the most likely failure mode, see Gross and Seelig (2011).

There are various techniques available to determine the Mode I fracture toughness of a material, which rely on different experimental geometries. In the present investigation the K_{Ic} values of Antarctic ice were obtained at $-15\,^{\circ}\mathrm{C}$ using the four-point bending technique, shown schematically in Fig. 5. Due to the geometry of the experimental arrangement, the sample in the vicinity of crack tip is in a state of pure bending, which results in a tensile stress at the crack tip. Experiments were carried out according to the ASTM (2008) E 1820-08 standard. During testing each notched sample was monotonically loaded to failure with a displacement u, measured with a linear variable differential transformer, which has a resolution of approximately ±150 nm (LVDT data). The resultant mechanical load F was found to increase approximately linearly with the displacement and was measured by a load cell with a resolution of approximately ±1 N (load cell data). The displacement, load and time were measured at a frequency of 50 Hz with a LabVIEW program.

Following sample preparation the ice sample was loaded to failure under displacement control with a rate of approximately $65\,\mu\mathrm{m\,s^{-1}}$, corresponding to a loading rate of $\sim 67\,\mathrm{N\,s^{-1}}$. Figure 6 displays representative force and displacement data as a function of time during a fracture experiment. It is apparent that both the displacement and force increase approximately linearly up to the point of fracture, defined as the maximum load prior to failure $P_{\max}$. After this load is reached, the crack grows and the sample fractures, resulting in the force instantaneously decreasing. The critical fracture toughness of each sample is determined using the maximum measured force, the sample geometry and the positioning of the loading rollers. The equations to calculate the fracture toughness for pure bending are derived from an elastic stress analysis and result are given here

$$K_{\mathrm{Ipb}} = f(a/W)\left[\frac{P_{\max}[S_{\mathrm{o}} - S_{\mathrm{i}}]10^{-6}}{BW^{3/2}}\right]\left[\frac{3[a/W]^{1/2}}{2[1-a/W]^{3/2}}\right] \tag{1}$$

where

$$f = f(a/W) \tag{2}$$

$$= 1.9887 - 1.326[a/W] - \frac{\{3.49 - 0.68[a/W] + 1.35[a/W]^2\}[a/W]\{1 - [a/W]\}}{\{1 + [a/W]\}^2} \tag{3}$$

and P_{max} is the maximum applied force, S_{o} the span of the outer rollers (S_{o} = 102.8 mm) and S_{i} the span of the inner rollers (S_{i} = 51.4 mm). The dimension B is perpendicular to the crack depth, W the dimension parallel to the crack depth and a is the notch depth. For details see ASTM (2007).

3 Results and discussion

During experimental characterization, 108 samples were measured. Of these samples, 91 failed due to a crack emanating from the notch; the other samples broke in at another position away from the notch, most likely due to a local defect that resulted in a higher stress intensity factor than at the notch. During analysis, only the samples that failed at the notch were used to calculate the fracture toughness. The average critical fracture toughness was found to be 95.35 kPa $\mathrm{m}^{1/2}$ with an average standard deviation of ±16.69 kPa $\mathrm{m}^{1/2}$ for a density variation from 844.5 to 870.3 kg m^{-3} (Fig. 7). In Fig. 7, each red circle represents an individual measurement; the average toughness for each density from the middle section of the 9 cylinders (see Fig. 2) is depicted by green squares with error bars that correspond to a 10 % deviation. The new results derived for Antarctic inland ice are compared in Fig. 7 with the results obtained by Schulson and Duval (2009), shown by blue diamonds. It can be clearly observed that the critical stress intensity values from Schulson and Duval (2009) are approximately 30–50 % larger than the average values determined by the four-point bending experiments. This could be due to a higher loading rate, a larger notch radius or differences in the type of the tested ice. Nevertheless, the distribution of the critical fracture toughness values is relatively small, demonstrating the repeatability of the current measurements. Additionally, the investigation of the sample thickness, the sample width and the location of the sample reveal that their influence on the results were negligibly small.

4 Conclusions

The critical stress intensity factor of ice was experimentally determined for glacial ice from Antarctica. During testing single edge v-notch beam samples in a four-point loading configuration were utilized and monotonically loaded to failure. The investigated density range was too small to conclusively observe a density-dependent change in the fracture toughness. In total, 91 samples were investigated, allowing for the determination of an average critical stress intensity and a standard deviation, determined to be $95.35\,\mathrm{kPa\,m^{1/2}}$ and $\pm 16.69\,\mathrm{kPa\,m^{1/2}}$, respectively. Comparison to previous experimental results (Schulson and Duval, 2009) shows good agreement, particularly when the variations in the ice sample and different testing conditions are considered. The samples are sawed and tested in only three days and due to the small dimension of a sample the loss of material is minimized. The distribution of the critical fracture toughness was shown to be very small in comparison with other materials. For further research, the density interval should be extended by analyzing different depths in one or more drill cores. This would provide a better statistical evaluation of the possible critical fracture toughness values. Different locations, such as ice from Greenland firn cores with different impurities or regions where the ice is known to be more anisotropic, could give further summary of the possible variation in fracture toughness values.

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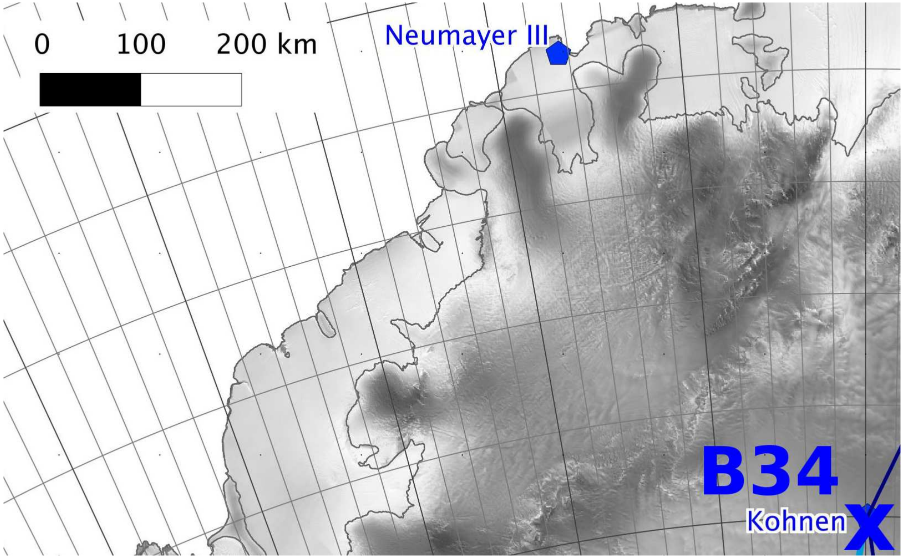

Figure 1. Location of the examined ice core B34.

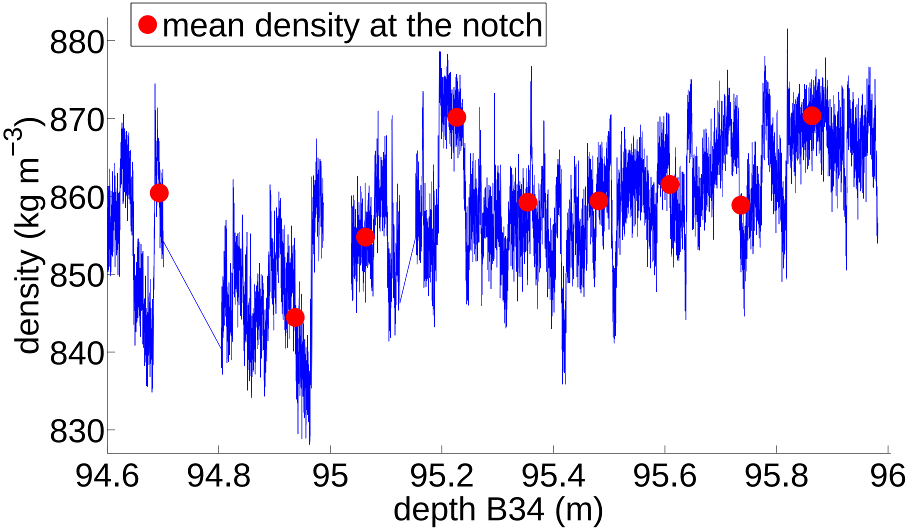

Figure 2. Depth-density profile of the considered ice core part.

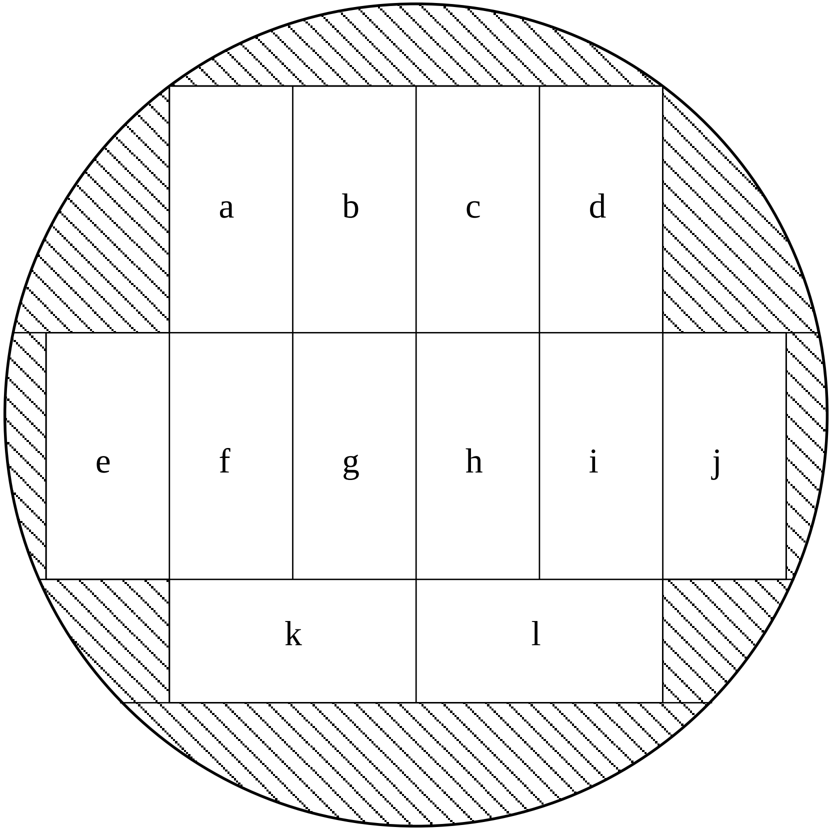

Figure 3. Cross section of ice core showing the sample location pattern.

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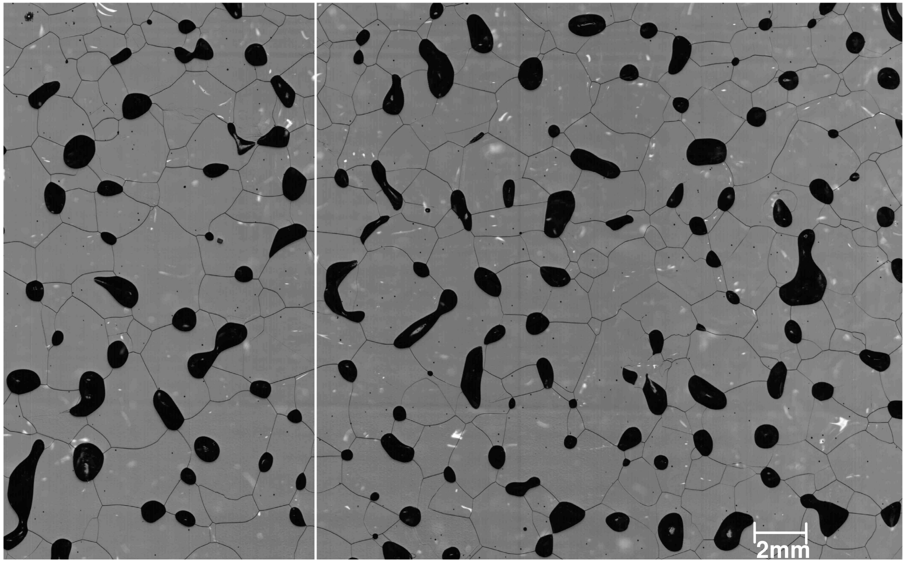

Figure 4. Representative microstructure of the B34 ice core showing air bubbles (black inclusions), grain boundaries (black lines) and the examplary white line, where the grain size was measured.

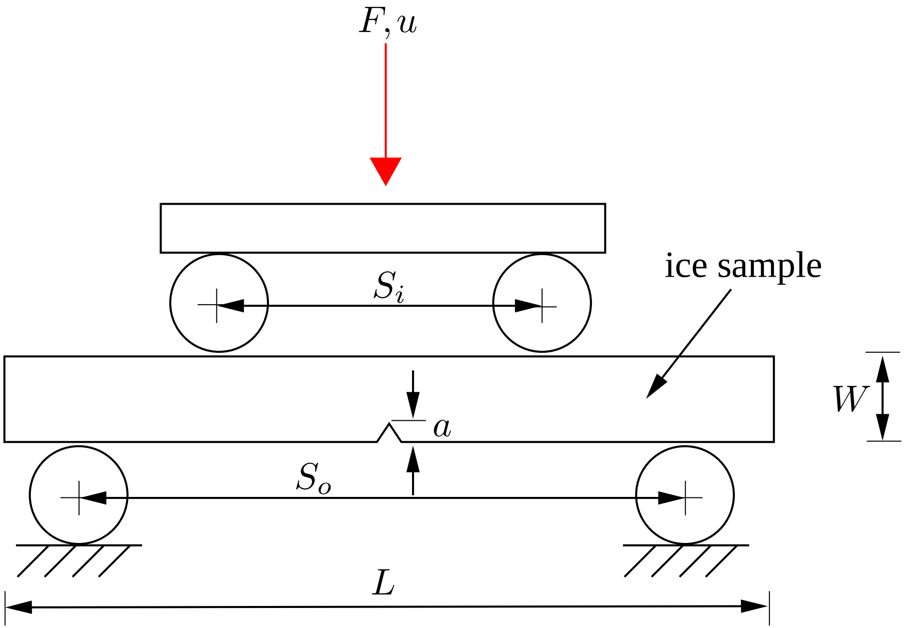

Figure 5. Schematic of four-point bending arrangement used to determine the critical fracture toughness.

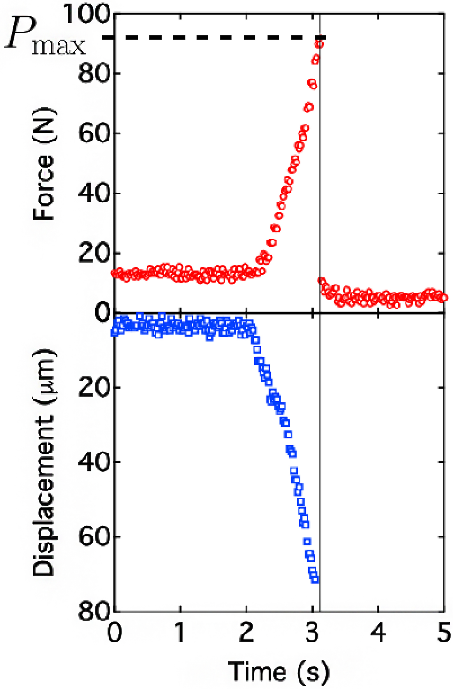

Figure 6. Representative force and displacement data as a function of time during a fracture experiment. The vertical thin black line reprents the time at failure.

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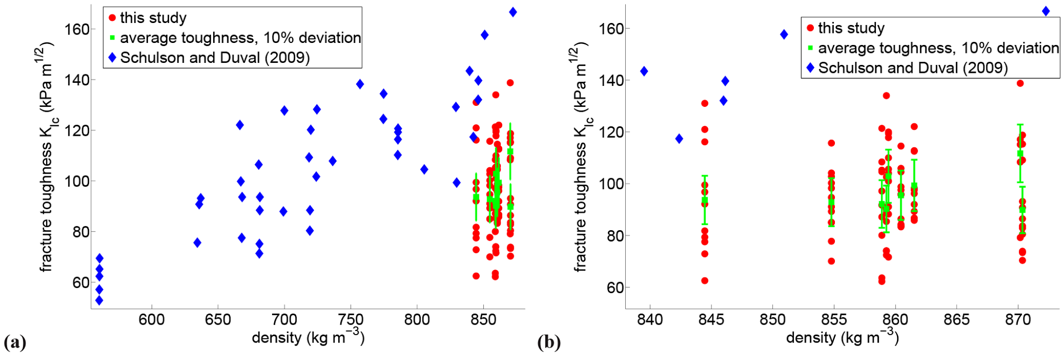

Figure 7. (a) Comparision to results from Schulson and Duval (2009) and the average of the measured fracture toughness values. **(b)** Detail magnification of the measured range.