ESTIMATING DRY SNOW DENSITY FROM GRAIN FORM AND HAND HARDNESS

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ABSTRACT: Snow density has many applications in avalanche forecasting, including calculations of load over weak layers. However, density measurements of snowpack layers are often incomplete because of problems sampling thin layers or time constraints on fieldwork. This paper summarizes over 5000 density measurements of dry snow from the Columbia and Rocky Mountains of Western Canada between 1993 and 2000. The density values are regressed on hand hardness to yield a method for estimating density of snow layers with known grain form and hand hardness. Standard errors give an indication of the quality of the estimate.

KEYWORDS: snow density; density estimation; hand hardness; grain form; avalanche forecasting

1. INTRODUCTION

Occasionally it may be necessary to estimate the density of a snow layer. Density measurements in the field may not be done due to time constraints or because a layer is too thin for the sampler. Having a complete set of density values is important for calculations of load over a weak layer, or for determining the water-equivalent of the snowpack.

Hand hardness measurements (Colbeck and others, 1990; CAA, 1995) are widely used and are quickly and consistently done during snow profiles. Likewise, snow grain forms are also usually recorded. This paper explores a method for estimating snow density from hand hardness and grain form. In an effort to increase the precision of the density estimates, this study differentiates between snow grain types.

2. METHODS

Densities were measured using a 100 cm^3 sampling tube and either a portable electronic scale or a Strong Stitch mechanical scale. Samples were taken vertically for layers at least as thick as the length of the sampling tube (10 cm) and horizontally for thinner layers. Layers thinner than the diameter of the sampling tube (4 cm) were not sampled or used in this study.

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Hand hardness classes (Colbeck and others, 1990; CAA, 1995) were determined by pushing into the snow with a fist in glove (F), four fingers in glove (4F), one finger in glove (1F), blunt end of pencil (P) or knife blade (K) with a constant manual force. The specified force is 10-15 N (1.0-1.5 kg force) but field workers rarely check their "standard" force with a force gauge.

Corresponding snow grain type and hand hardness values were recorded for each layer with a density measurement. The snow types were recorded by either their major or minor classification (Colbeck and others, 1990). Hand hardness classes F, 4F, 1F, P, K and I (CAA, 1995) were subclassified using the 16 levels: F-, F, F+, 4F-, 4F, 4F+, 1F-, 1F, 1F+, P-, P, P+, K-, K, K+, I, where the + and – subclasses require slightly less or slightly more force than the respective main class.

The hand hardness classes were assigned a corresponding hand hardness index. Fist (F) is assigned an index value of 1 and each major class is incremented by 1, with intermediate values for the subclasses. The hand hardness index is described in more detail later in this paper.

The data presented in this paper are from measurements of 5411 snow layers taken in the Purcell, Selkirk, Monashee and Rocky Mountain Ranges of western Canada between 1993 and 2000. Measurements were done by at least 27 different people.

Table 1: Measured density (kg/m^3) of common snow types grouped by hand hardness and grain type.
N - number of layers measured, SD - standard deviation, SE - standard error.

Hand Hardness	Hand hardness index	Precipitation particles (PP) 1abcde				Graupel (gp) 1f				Decomposing and Fragmented precipitation particles (DF) 2ab				Rounded grains (RG) 3ab				Rounded mixed forms (RGmx) 3c			
		N	**Mean**	SD	SE	N	**Mean**	SD	SE	N	**Mean**	SD	SE	N	**Mean**	SD	SE	N	**Mean**	SD	SE
F-	0.67	89	**64**	22	2	2	**91**	32	23	54	**81**	23	3	~	~	~	~	1	**81**	~	~
F	1.00	206	**83**	29	2	13	**133**	29	8	352	**103**	26	1	17	**167**	40	10	4	**155**	40	20
F+	1.33	24	**102**	25	5	~	~	~	~	84	**115**	30	3	4	**169**	13	6	3	**160**	31	18
4F-	1.67	6	**118**	25	10	1	**164**	~	~	73	**121**	28	3	12	**147**	23	7	3	**163**	26	15
4F	2.00	31	**113**	28	5	6	**138**	37	15	344	**135**	30	2	91	**169**	40	4	7	**175**	18	7
4F+	2.33	5	**114**	14	~	2	**157**	33	~	110	**143**	31	3	51	**174**	33	5	3	**196**	15	9
1F-	2.67	2	**138**	29	~	2	**203**	74	53	73	**156**	31	4	73	**185**	36	4	5	**230**	56	25
1F	3.00	6	**154**	50	20	11	**169**	45	14	235	**169**	32	2	451	**204**	40	2	22	**205**	23	5
1F+	3.33	~	~	~	~	~	~	~	~	53	**189**	36	5	204	**219**	42	3	21	**215**	38	8
P-	3.67	~	~	~	~	~	~	~	~	27	**215**	32	6	256	**243**	41	3	16	**250**	29	7
P	4.00	1	**178**	~	~	5	**267**	39	17	40	**210**	39	6	740	**272**	47	2	19	**266**	28	6
P+	4.33	~	~	~	~	~	~	~	~	4	**237**	74	37	266	**310**	51	3	3	**299**	12	7
K-	4.67	~	~	~	~	~	~	~	~	~	~	~	~	46	**365**	48	7	~	~	~	~
K	5.00	~	~	~	~	~	~	~	~	~	~	~	~	28	**377**	60	11	~	~	~	~
K+	5.33	~	~	~	~	~	~	~	~	~	~	~	~	5	**418**	38	17	~	~	~	~

Hand Hardness	Hand hardness index	Faceted crystals (FC) 4ab				Faceted mixed forms (FCmx) 4c				Depth hoar (DH) 5abc				Wet Grains (WG) 6ab				Melt-freeze crust (mfc) 9e			
		N	**Mean**	SD	SE	N	**Mean**	SD	SE	N	**Mean**	SD	SE	N	**Mean**	SD	SE	N	**Mean**	SD	SE
F-	0.67	3	**125**	10	~	~	~	~	~	~	~	~	~	1	**45**	~	~	~	~	~	~
F	1.00	46	**143**	36	5	2	**165**	16	~	7	**202**	40	15	2	**216**	141	100	~	~	~	~
F+	1.33	7	**149**	23	9	1	**155**	~	~	~	~	~	~	1	**220**		~	~	~	~	~
4F-	1.67	2	**159**	11	~	1	**134**	~	~	~	~	~	~	2	**189**	86	61	~	~	~	~
4F	2.00	88	**215**	41	4	13	**222**	59	16	17	**241**	30	7	16	**231**	86	21	~	~	~	~
4F+	2.33	19	**218**	42	10	8	**208**	24	8	6	**258**	42	17	1	**126**	~	~	~	~	~	~
1F-	2.67	28	**244**	39	7	19	**222**	30	7	5	**243**	27	12	4	**200**	70	35	~	~	~	~
1F	3.00	154	**255**	45	4	60	**248**	37	5	18	**256**	56	13	15	**266**	100	26	3	**332**	16	~
1F+	3.33	38	**268**	40	6	32	**252**	53	9	2	**283**	46	33	5	**319**	17	7	1	**284**	~	~
P-	3.67	38	**282**	37	6	68	**285**	36	4	~	~	~	~	3	**319**	47	27	3	**278**	27	16
P	4.00	122	**289**	47	4	121	**308**	44	4	8	**297**	31	11	8	**278**	54	19	16	**286**	42	10
P+	4.33	16	**331**	45	11	49	**348**	43	6	1	**268**	~	~	5	**311**	68	~	8	**282**	75	26
K-	4.67	5	**314**	45	20	12	**386**	32	9	1	**320**	~	~	~	~	~	~	6	**304**	68	28
K	5.00	~	~	~	~	6	**368**	49	20	1	**270**	~	~	~	~	~	~	17	**296**	64	16
K+	5.33	~	~	~	~	2	**446**	8	6	~	~	~	~	~	~	~	~	1	**276**	~	~

3. OBSERVATIONS

Grain forms are grouped or broken down into subsets (Table 1) as follows: Precipitation particles (PP) include all subclasses except graupel, hail and ice pellets. Graupel (PPgp) is given its own category due to its significantly different form and properties. Hail and ice pellets are excluded because only one data value is available for each. Decomposing and fragmented precipitation particles (DF) include both subclasses. The mixed forms of rounded grains (RGmx) and facets (FCmx) are not included under their major classes; each is given their own category. Depth hoar (DH) and wet grains (WG) include all of their subclasses. Surface hoar layers were too thin for the sampling tube and are therefore omitted. Data for ice masses are limited to four layers and also excluded. For surface deposits and crusts only melt-freeze crusts (mfc) are included in this study; no data are available for the other subclasses.

Table 1 shows that for a given hardness, more mature grain types are typically denser than less mature forms. Consider layers of 4F hardness: New snow (PP) layers have a mean density of about 117 kg/m^3 whereas layers of decomposed and fragmented particles have a mean density of about 138 kg/m^3. Further, 4F layers of rounded grains have a mean density of about 169 kg/m^3.

4. ANALYSIS

While Table 1 can be used to estimate density from grain type and hand hardness, better estimates are probably possible based on a regression that reflects the monotonic effect of densification on hardness for a particular grain type. For a regression we need a measure of hardness with interval properties.

Similar work in this area (Gold, 1956; Kinosita, 1960) established relationships between hardness and density, with the hardness of snow defined as penetrating force over area of a blunt penetrometer (Kinosita 1960). Using the specified force of 10 to 15 N (1.0 to 1.5 kg force), and average measurements of area for the major hand hardness classes as shown in Table 2, it is possible to arrive at approximate hardness values for the hand hardness classes. The areas of the major hand hardness classes were determined by averaging the two reasonable extremes of a large hand with a bulky glove and a small hand with a thin glove. The parts that would come into contact with the snow were measured with a ruler.

Table 2: Average area measurements and approximate hardness for the major hand hardness classes.

Hand hardness class	Hand hardness index	Area cm^2	Hardness (kN/m^2)
F	1	82	1.5
4F	2	22.5	5.6
1F	3	5	25
P	4	0.64	195
K	5	0.15	833

The values in Table 2 corroborate Brown's (1995, personal communication) suggestion that for the hand hardness test, the area of the penetrometer (fist, fingers, etc.) decreases step-wise by a factor of four (roughly) for the classes F, 4F, 1F, P and K.

Jamieson (1995) used a factor of two for a hand hardness index, in an analysis of an earlier and smaller version of our data set. However, those results, as well as trials with a factor of four, did not fit our data as well as the hand hardness index.

For our analysis, we let the hand hardness H (with units of force over area) increase step-wise by a factor M (corresponding to a decrease in area of 1/M). Using Fist resistance as base

$$H = (F_{CONSTANT}/A_{FIST})\, M^{h-1} \qquad (1)$$

where $F_{CONSTANT}$ is the approximately constant force applied manually, A_{FIST} is the area of a gloved fist, and h = 1, 2, 3, 4, 5 is the hand hardness index in Tables 1 and 2 for classes F, 4F, 1F, P and K, respectively.

Kinosita (1960) found a linear relationship between log hardness and density. Similarly, Gold (1956) found a linear relationship for low density snow between log hardness and density.

$$\text{Log } H = C_1 + C_2\, \rho \qquad (2)$$

Combining Equation 1 and Equation 2, we obtain a linear relation between h and ρ

$$\text{Log} (F_{CONSTANT}/A_{FIST}) + (h\text{-}1) \text{ Log } M = C_1 + C_2 \rho \quad (3)$$

For each grain type, the density is regressed on the hardness index h for groups of grain types using the following simplification of Equation 3

$$\rho = A + B\,h \quad (4)$$

Of course, the test of this linear relationship will be how well it fits real data. The empirical constants, A and B, the coefficient of determination, R^2, and the standard error of estimation, s, and the significance level, p, are given in Table 3.

Wet grains, due to their dependence on liquid water content, and melt-freeze crusts exhibit unacceptably large error values and are not included in further tables or figures.

Using the empirical constants, A and B, from Table 3 the estimated density values are plotted (Figure1a and 1b) along with the measured means from Table 1.

Rounded grains do not conform well to a linear regression. Instead, we used a non-linear regression of the form

$$\rho = A + B\,h^x \quad (5)$$

This yields a better fit ($R^2 = 0.54$) and the empirical constants: A = 154, B = 1.51, and x = 3.15.

Table 3: Linear regressions of density on hardness index h by groups of grain types

Class	No. of Layers	A	B	R^2	p	s
PP	370	45	36	0.30	< 10E-16	27
PPgp	42	83	37	0.47	4.63E-07	42
DF	1449	65	36	0.52	< 10E-16	30
RG	2244	0.79	69	0.50	< 10E-16	46
RGmx	107	91	42	0.55	< 10E-16	32
FC	566	112	46	0.51	< 10E-16	43
FCmx	394	56	64	0.51	< 10E-16	43
DH	66	185	25	0.26	1.287E-05	41

In Figures 1a and 1b, estimated values are only given to the extent of the measured means.

Except for rounded grains, the linear regression lines show a reasonable fit to the data, implying a linear relationship between density and the hardness index h. The linear relationships support the assumptions behind Equations 1 to 4, including the interval property assumed for h.

Note that the lines, especially those in Figure 1a, do not represent densification, since during densification grains may change form. For example, under conditions of low temperature gradient, new snow particles (PP) become decomposed particles (DF) which in time become rounded grains (RG).

Although there is a dependency on temperature (Gold, 1956; Kinosita, 1960) for hardness, the effect is much less significant than the density/hardness relationship. Considering the relatively low accuracy of hand hardness measurements, temperature effects would not be readily apparent and are not covered in this paper.

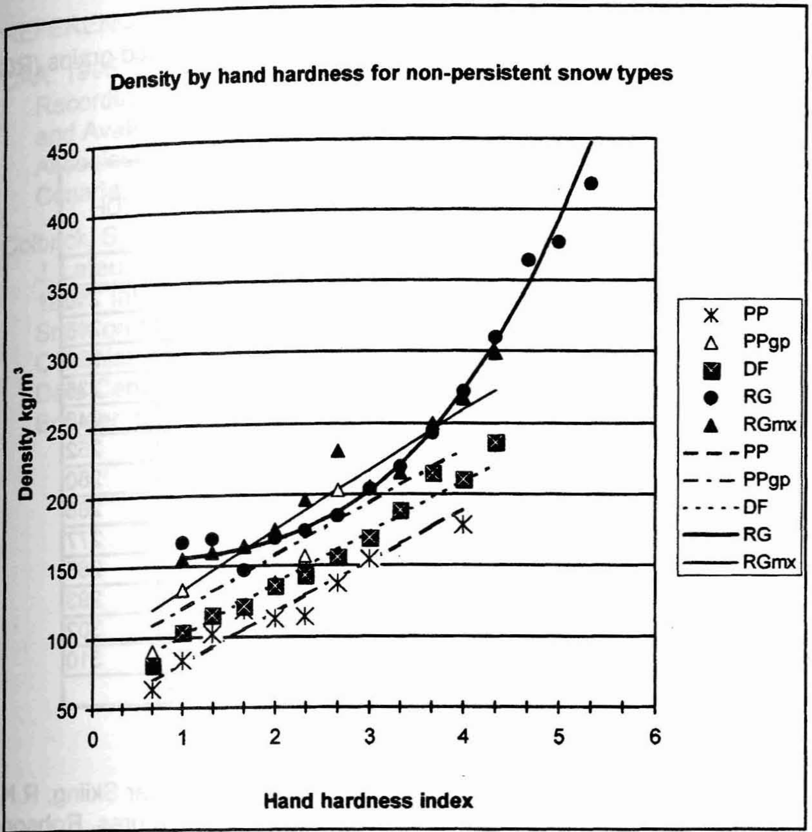

Figure 1a: Density by hand hardness for non-persistent snow types. Points represent measured means, lines represent estimated values from regressions.

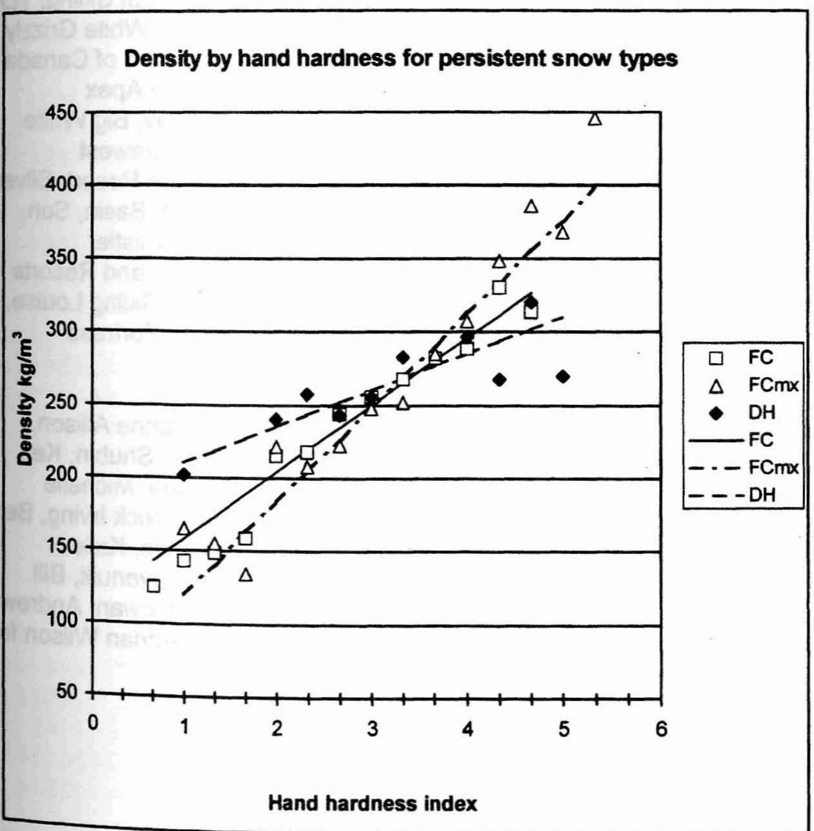

Figure 1b: Density by hand hardness for persistent snow types. Points represent measured means, lines represent estimated values from regressions.

Table 4: Calculated densities (kg/m^3) using the regressions from Table 3, except for rounded grains (RG) which are derived from the non-linear Equation 5.

Hand hardness	Hand hardness index	PP	PPgp	DF	RG	RGmx	FC	FCmx	DH
F-	0.67	69	108	89		119	143		
F	1.00	81	120	101	156	133	158	120	210
F+	1.33	93	132	113	158	147	173	141	218
4F-	1.67	105	145	125	162	161	189	163	227
4F	2.00	117	157	137	167	175	204	184	235
4F+	2.33	129	169	149	176	189	219	205	243
1F-	2.67	141	182	161	187	203	235	227	252
1F	3.00	153	194	173	202	217	250	248	260
1F+	3.33	165	206	185	221	231	265	269	268
P-	3.67	177	219	197	244	245	281	291	277
P	4.00	189	231	209	273	259	296	312	285
P+	4.33			221	306	273	311	333	293
K-	4.67				347		327	355	302
K	5.00				393			376	310
K+	5.33				447			397	

5. APPLICATION

Table 4 presents the estimated densities from the regression lines in Figures 1a and 1b. These values can be used to estimate a density for a given hand hardness and snow type, keeping in mind the accuracy of the estimates indicated by *s* in Table 3. We use the non-linear Equation 5 for rounded grains (RG) and the linear Equation 4 for other grain types. For estimation of load due to particular layers, the accuracy of the estimate decreases with an increase in the thickness of the layer.

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