ESTIMATING THE DENSITY OF DRY SNOW LAYERS FROM HARDNESS, AND HARDNESS FROM DENSITY

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ABSTRACT: At the ISSW 2000, Geldsetzer and Jamieson presented empirical relations between the density and hardness of dry snow layers for common grain types. These relations have been widely used to estimate density and water equivalent (e.g. because the layer was too thin for the density sampler), and to estimate the hardness of layers in snowpack evolution models. Since 2000, the database of snow layers has tripled to over 15,000 layers of dry snow with measured density, hardness, and grain size. This paper will update the relationships so that grain size (for specific grain types) can be better used to estimate density from hardness, and hardness from density.

KEYWORDS: grain size, snow density, grain type, snow hardness, avalanche forecasting, snow stratigrapy

1. INTRODUCTION

Having information on the density of a snow layer can be quite beneficial for practitioners today. Density is used to calculate the load over a weak layer as well as for determining the water-equivalent of the snowpack. Furthermore, it can improve slab load calculations and thereby aid avalanche forecasting. Due to their limited time in the snow pits, practitioners sometimes rely on a table that gives the relationship between density, hand hardness, and grain type, but this is just a coarse estimate.

In 2000, Geldsetzer and Jamieson helped to improve the density estimation by relating density with hardness for common grain types. Since the publication of their paper "Estimating Dry Snow Density from Grain Form and Hand Hardness", ASARC's database of snow layers has tripled to over 15,000 layers. This paper will update the relationships as well as incorporate grain size for specific grain types into the analysis.

2. METHODS

Density was measured using a 100 cm^3 sampling tube and either a portable electronic scale or a tilting scale. Samples were taken vertically for layers with a thickness of at least 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.

Corresponding snow grain type and hand hardness values were recorded for each layer with a density measurement.

The hand hardness of each layer was rated 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 of force) but field workers rarely check their "standard" force with a force gauge.

Hand hardness classes F, 4F, 1F, P, K and I 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 more or slightly less force than the respective main class.

The hand hardness classes were assigned a corresponding hand hardness index. Fist (F) was assigned an index value of 1 and each major class was incremented by 1 (Fierz et al., 2009), with intermediate values for the subclasses.

The data presented in this paper are from measurements of 15,061 dry snow layers taken in the mountains of western Canada, mostly in the Columbia Mountains.

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

Hand Hardness	h	Precipitation particles (PP)				Graupel (PPgp)				DF				Rounded grains (RG)				Faceted rounded particles (RGxf)			
		N	**Mean**	SD	SE	N	**Mean**	SD	SE	N	**Mean**	SD	SE	N	**Mean**	SD	SE	N	**Mean**	SD	SE
F-	0.7	269	**63**	22	1	9	**82**	17	6	171	**83**	25	2	3	**185**	64	37	5	**106**	19	10
F	1.0	493	**83**	27	1	38	**124**	30	5	963	**102**	29	1	78	**145**	56	6	27	**138**	34	7
F+	1.3	78	**108**	28	3	12	**117**	16	5	357	**115**	31	2	48	**147**	37	5	15	**155**	38	10
4F-	1.7	24	**114**	24	5	6	**116**	34	14	277	**123**	28	2	58	**146**	32	4	16	**162**	43	11
4F	2.0	82	**117**	29	3	19	**139**	34	8	965	**136**	30	1	300	**166**	39	2	26	**178**	40	8
4F+	2.3	22	**120**	32	7	9	**161**	56	19	320	**148**	32	2	225	**174**	32	2	17	**188**	28	7
1F-	2.7	4	**150**	22	11	4	**219**	50	25	242	**158**	35	2	305	**191**	39	2	22	**216**	61	13
1F	3.0	12	**159**	36	10	20	**181**	51	12	576	**172**	33	1	1168	**206**	39	1	54	**215**	37	5
1F+	3.3	1	**260**	~	~	8	**204**	23	8	142	**189**	36	3	753	**225**	41	2	33	**229**	42	7
P-	3.7	1	**178**	~	~	3	**320**	119	69	63	**212**	32	4	713	**251**	42	2	30	**254**	38	7
P	4.0	1	**178**	~	~	10	**268**	36	11	76	**223**	46	5	1647	**273**	47	2	39	**272**	37	6
P+	4.3	~	~	~	~	~	~	~	~	11	**262**	54	16	690	**311**	49	2	11	**321**	41	12
K-	4.7	~	~	~	~	~	~	~	~	1	**348**	~	~	88	**362**	46	5	~	~	~	~
K	5.0	~	~	~	~	~	~	~	~	~	~	~	~	53	**372**	58	8	~	~	~	~
K+	5.3	~	~	~	~	~	~	~	~	~	~	~	~	6	**415**	35	14	~	~	~	~

Hand Hardness	h	Faceted crystals (FC)				Rounding faceted particles (FCxr)				Depth Hoar (DH)				Melt Forms (MF)				Melt-freeze crust (MFcr)			
		N	**Mean**	SD	SE	N	**Mean**	SD	SE	N	**Mean**	SD	SE	N	**Mean**	SD	SE	N	**Mean**	SD	SE
F-	0.7	9	**133**	63	21	3	**129**	27	16	~	~	~	~	~	~	~	~	~	~	~	~
F	1.0	111	**148**	48	5	13	**158**	38	11	13	**232**	59	16	~	~	~	~	~	~	~	~
F+	1.3	23	**168**	48	10	11	**175**	30	9	4	**239**	48	24	~	~	~	~	~	~	~	~
4F-	1.7	31	**193**	47	8	26	**181**	49	10	6	**243**	29	12	2	**308**	13	9	~	~	~	~
4F	2.0	191	**210**	47	3	96	**193**	50	5	31	**252**	42	8	10	**191**	77	24	4	**297**	35	18
4F+	2.3	62	**223**	47	6	54	**198**	51	7	13	**261**	41	11	2	**232**	108	77	2	**278**	20	14
1F-	2.7	79	**238**	40	5	90	**226**	47	5	11	**257**	30	9	9	**216**	89	30	4	**204**	103	52
1F	3.0	294	**255**	49	3	262	**240**	42	3	29	**267**	52	10	18	**237**	72	17	13	**286**	45	2
1F+	3.3	94	**270**	41	4	184	**258**	51	4	4	**304**	37	18	6	**311**	32	13	15	**291**	50	13
P-	3.7	93	**289**	45	5	239	**278**	40	3	1	**453**	~	~	7	**306**	37	14	29	**279**	41	8
P	4.0	223	**298**	46	3	371	**303**	46	2	11	**304**	36	11	22	**294**	53	11	94	**297**	45	5
P+	4.3	47	**338**	44	6	174	**332**	45	3	1	**268**	~	~	11	**303**	54	16	72	**306**	54	6
K-	4.7	16	**387**	68	17	28	**367**	53	10	1	**320**	~	~	1	**312**	~	~	31	**306**	60	11
K	5.0	13	**329**	40	11	10	**376**	45	14	2	**214**	79	56	~	~	~	~	96	**308**	76	8
K+	5.3	~	~	~	~	3	**444**	7	4	~	~	~	~	~	~	~	~	2	**321**	63	45

3. DATA

Similar to Geldsetzer and Jamieson's analysis, the grain forms were broken down and grouped by snow types (Table 1). Precipitation particles (PP) include all subclasses except hail, ice pellets, rime, and graupel. Since graupel (PPgp) has different properties and form from PP, it was given its own category. Decomposing and fragmented precipitation particles (DF) include all its subclasses. Rounded grains (RG) include all its major classifications excluding faceted rounded particles (RGxf), and wind packed. Facets (FC) include all its subclasses excluding rounding faceted particles (FCxr), which was given its own category. Melt forms (MF) and depth hoar (DH) includes all of the respective subclasses.

Comparing Table 1 with the Table 1 in Geldsetzer and Jamieson's 2000 paper, less data are reported for some hand hardness classes of melt forms. This is likely due to problems transferring data between databases.

The data for the melt-freeze crust came from two different databases. The first database was the ASARC database and the other came from Ryan Buhler, who in 2013 wrote a thesis on the melt-freeze crusts. Buhler improved on the estimation of crust density by isolating a piece of the melt freeze crust into a rectangular block. This sample was taken from a layer where the thickness was a good representation of the layer across the exposed pit wall. All the dimensions of the crust including mass were measured to calculate the volume, and eventually density (Buhler, 2013).

It is important to note that some of Buhler's individual crusts had a range of hand hardness, e.g. 1F to P. For cases where the range of hardness was recorded, the ranges were broken down to include just the major hardness index for the analysis. Listed below are the following ranges that were assigned in the database followed by their respective hardness:

- 1F to P was assigned the hand hardness P.
- P to K was assigned the hand hardness K.
- P to P+ was assigned the hand hardness P.

The graph of density versus hand hardness for the melt-freeze crust is shown in Figure 1 with its range of densities as well as its mean density.

4. RESULTS

4.1 Linear Regression

Although Table 1 allows us to estimate the density of a snow grain type given specific hand hardness, a better density estimation can be made through the use of linear regression.

For each grain type, the density was regressed on the hardness index *h* for groups of grain types. All grain types except rounded grains followed a linear relationship between density and hand hardness, and have the form

$$\rho = A + Bh \qquad (1)$$

Rounded grains show an exponential relationship between density and hand hardness and have the form

$$\rho = Ae^{Bh} \qquad (2)$$

This yielded a better fit of $R^2 = 0.55$.

The empirical constants, A and B, the coefficient of determination, R^2, the standard error of estimation, SE, the significance level p, and the 10^{th} and the 90^{th} percentiles for hardness is shown in Table 2.

Table 2 updates on the regressions made by Geldsetzer and Jamieson in their 2000 paper, and Table 3 presents the estimated density from the regression equations shown in Table 2.

For estimation of the load due to particular layers, the accuracy of the estimate decreases with an increase in the thickness of the layer.

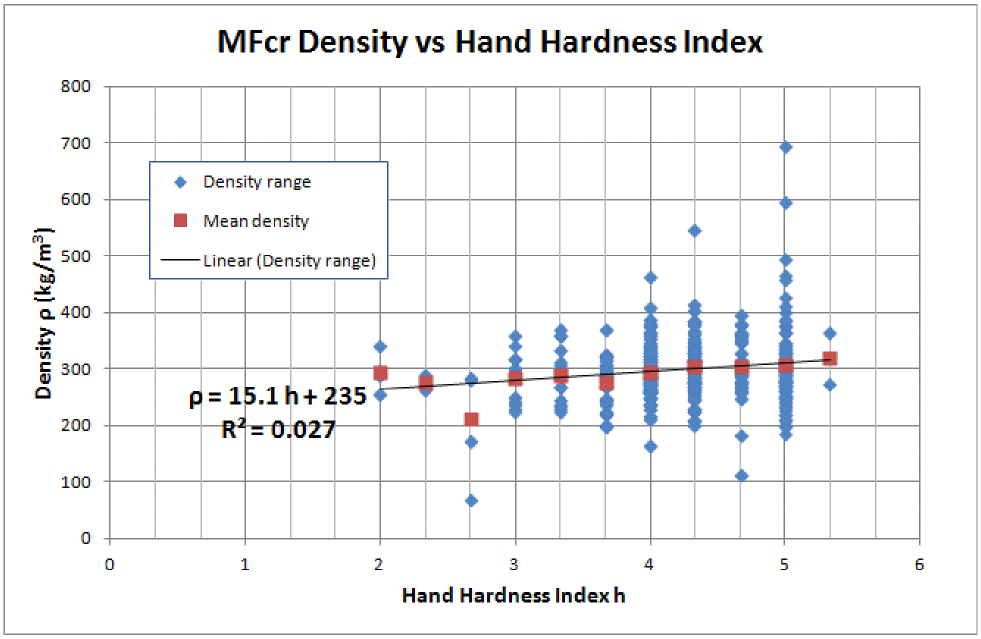

Figure 1: Density by hand hardness for the melt-freeze crusts

Table 2: Linear regressions of density on hand hardness index by grain types (Equation 1), except for a non-linear regression for RG (Equation 2)

Grain Type	No. of Layers	A	B	R^2	SE	p	Percentile Hardness 10th	Percentile Hardness 90th
PP	987	41.3	40.3	0.35	27	$< 10^{-16}$	F-	4F
PPgp	138	61.8	46.4	0.55	43	$< 10^{-16}$	F	1F+
DF	4163	62.5	37.4	0.50	31	$< 10^{-16}$	F	1F
RGxf	295	85.0	46.3	0.58	40	$< 10^{-16}$	F	P
FC	1286	103	50.6	0.53	47	$< 10^{-16}$	F+	P
FCxr	1564	68.8	58.6	0.50	46	$< 10^{-16}$	4F+	P+
DH	127	214	19.0	0.12	48	10^{-4}	F	P
MFcr	362	235	15.1	0.027	58	10^{-4}	1F+	K
RG	6135	91.8	0.270	0.55	0.2	$< 10^{-16}$	4F+	P+

Table 3: Calculated densities (kg/m^3) using the regressions from Table 2

Hand Hardness	h	PP	PPgp	DF	RG	RGxf	FC	FCxr	DH	MFcr
F-	0.7	68	93	88	110	116	137	108		
F	1.0	82	108	100	120	131	154	127	233	
F+	1.3	95	124	112	132	147	170	147	239	
4F-	1.7	109	139	125	144	162	188	167	246	
4F	2.0	122	155	137	158	178	204	186	252	265
4F+	2.3	135	170	150	172	193	221	205	258	270
1F-	2.7	149	186	162	189	209	238	225	265	275
1F	3.0	162	201	175	206	224	255	245	271	280
1F+	3.3	176	216	187	226	239	271	264	277	285
P-	3.7	189	232	200	247	255	289	284	284	290
P	4.0	203	247	212	270	270	305	303	290	295
P+	4.3			224	296	285	322	323	296	300
K-	4.7			237	324		339	343	303	306
K	5.0				354		356	362	309	311
K+	5.3				387			381		315

4.2 Grain Size

The strength of snow is a highly variable property that not only depends on density, but other properties such as grain size and temperature (Gold, 1956). As a result, the use of grain size was considered to better estimate the density of different grain forms. Grain size for each layer was calculated by taking the average of the minimum and maximum grain size.

For each grain type, density was regressed on grain size for a fixed hardness. Most of the regressions showed a very weak relationship between grain size and density. Due to the large number of graphs corresponding to this regression, only two graphs, one with a poor fit, and one with a better fit are shown. Figure 2 is an example of a regression that can be used for the estimation of density. The range of predicted density values is greater than the standard error. Figure 3 is an example of a poor fit, in which the standard error is greater than the range of density.

Table 5 summarizes the numerous regressions of density on grain size for a fixed hardness and grain type. To simplify the table, the hardness values were grouped into major hardness classifications instead of having subclasses for each group. Only grain types with a significant correlation between density and grain size for a given hardness were included in the table. Faceted rounded particles were excluded from the analysis since it had only one recorded value for grain size. The trend that can be observed from the table is that younger grains have a negative correlation between density and grain size, while the older grains show a positive correlation. One possible explanation is that older grains are likely to have a larger bond whereas the younger grains are likely to have a smaller bond. Another possible explanation can be made through the use of the Brun Triangle for dendricity (Brun et al, 1992). Dendricity describes the original crystal shape, e.g. arms, that remains in a snow layer, and is given a value from 1 to 0. Figure 4 shows the relationship between dendricity and grain type. The Brun Triangle isolated the different grain types based on dendricity, which helped to explain the trend that older grains followed a positive relationship between density and grain size, while the younger grains followed a negative trend.

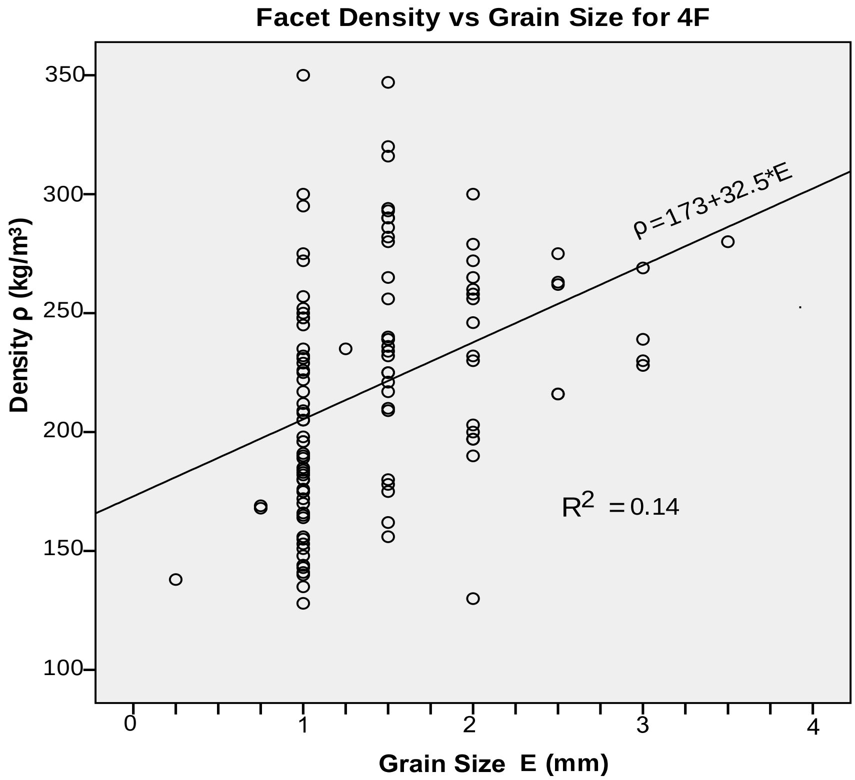

Figure 2: Facet density for 4F hardness versus grain size. Predicted range = 105, SE = 46 kg/m^3

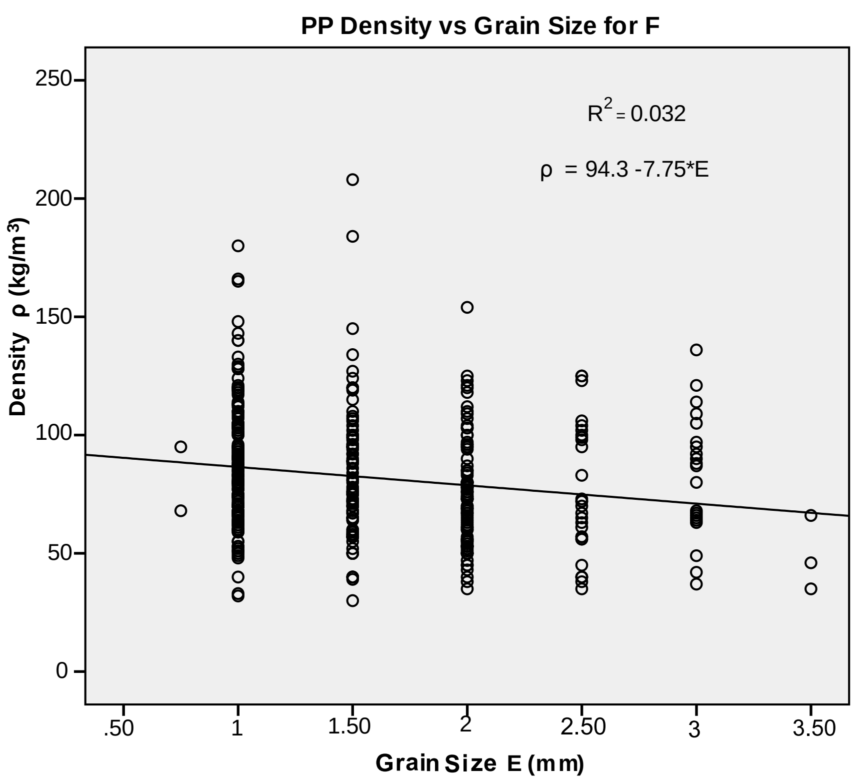

Figure 3: PP density for F hardness versus grain size Predicted range = 21, SE =26 kg/m^3

Table 4: Significant correlation between density and grain size for a given hardness and grain type

	PP	PPgp	DF	RG	FC	FCxr
K Group						
P Group				+		+
1F Group		+			+	+
4FGroup		+	-	-	+	+
F Group	-		-		+	

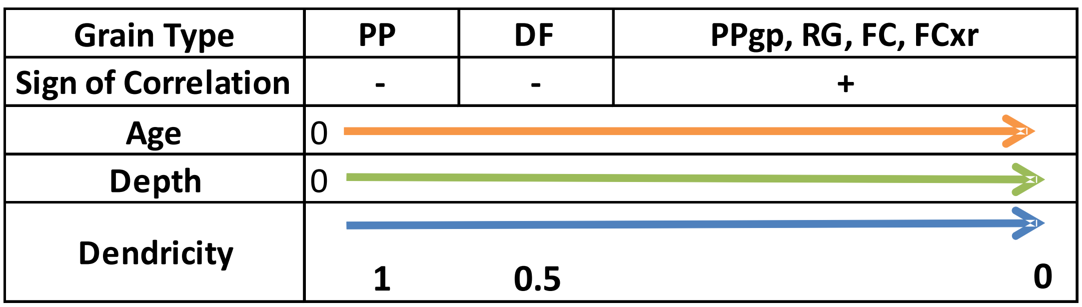

Figure 4: Sign of correlation from Table 5 and relation to age, depth, and dendricity for various grain types

4.3 *Multivariable Linear Regression*

Although the regressions above are significant, they are not as good of a tool for predicting density since grain size, density, and hardness are interrelated. Multivariable linear regressions are used to better estimate density.

For Table 5, hand hardness was regressed on density ρ and grain size

$$h = A\rho + BE + C \quad (4)$$

while for Table 6, density was regressed on hand hardness and grain size E.

$$\rho = Ah + BE + C \quad (5)$$

Both tables show only significant regressions, along with its significance level, and the 10th and 90th percentile for both the grain size and the hardness.

Due to high standard error values for the regressions in Table 6, users should decide whether or not they want to use the regression to estimate density.

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Table 5: Significant multivariable linear regression of hardness index on density and grain size (Equation 4)

								Percentile			
								Grain Size		Hardness	
Grain Type	No. of Layers	A	B	C	Adjusted R^2	SE	p	10th	90th	10th	90th
Facets	950	0.0101	-0.277	0.685	0.53	1	$< 10^{-16}$	1	2	4F-	P
FCxr	1210	0.00839	-0.381	1.56	0.51	1	$< 10^{-16}$	1	1.5	4F+	P+
RG	3151	0.00830	-0.0985	1.48	0.56	1	$< 10^{-16}$	0.75	1	4F+	P+

Table 6: Significant multivariable linear regression of density on hardness index and grain size by different groups of grain types (Equation 5)

								Percentile			
								Grain Size		Hardness	
Grain Type	No. of Layers	A	B	C	Adjusted R^2	SE	p	10th	90th	10th	90th
Facet	952	51.9	19.7	82.8	0.53	46	$< 10^{-16}$	1	2	4F-	P
FCxr	1212	60.4	27.7	36.7	0.50	45	$< 10^{-16}$	1	1.5	4F+	P+
PP	848	40.0	-7.33	52.8	0.39	25	$< 10^{-16}$	1	2.5	F-	4F
PPgp	109	38.8	18.8	35.7	0.64	33	$< 10^{-16}$	1	3.5	F	1F+
DF	3499	37.9	-8.87	71.4	0.52	31	$< 10^{-16}$	1	2	F	1F
MF	72	34.9	11.2	124.5	0.17	63	10^{-3}	1	4	4F+	P+

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