

## Article

# Sugar as an Analogue for Snow in Penetration Testing: A Preliminary Comparison

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**Abstract:** Snow is a sintered matrix of ice, the strength of which is determined by the number and size of bonds between ice grains. However, because snow is a thermally unstable material, it is problematic to transport and store samples for accurate ex situ testing of mechanical behaviour. As an analogue for snow, we examined the sintering behaviour of different types of granular sugar at different humidities over different temporal periods and then assessed the extent of sintering and resistance to penetration of these samples. Like snow, increased sintering occurs in sugar over time. Sintering extent and rate are affected by the humidity environment and penetration resistance generally increases after increased sintering time. This preliminary examination suggests that in the absence of snow testing facilities, humidity-controlled sintered sugar may serve as a valuable proxy for examining the temporal variation of penetration resistance in snow.

**Keywords:** snow; sugar; sintering; penetration testing



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## 1. Introduction

Understanding the mechanical properties of snow and ice is necessary for the efficient design and construction of cold regions infrastructure. Testing and evaluation is most commonly undertaken in situ or using samples within cold labs. However, there is an inevitable uncertainty as to the accuracy of results obtained from ex situ testing. Therefore, development of suitable proxies for snow, such as sugar or foam, is valuable, potentially enabling further research in this field. Snow has been specifically considered as a foam or a cellular solid by Brown [1], Petrovic [2] and others including Johnson [3]; Kirchner et al. [4] particularly examined the use of foam as a mechanical proxy for snow. Sugar is a crystalline particulate that sinters or bonds within different humidity environments, and fractures upon penetration; could sugar be a viable analogue for snow, for the purposes of mechanical testing?

In this paper, we briefly review the processes of sintering and then investigate the properties of sugar as an analogue for snow in penetration testing. We examine the sintering properties of three different types of sugar when subjected to different humidities over a thirty day period, and then we assess the resistance to penetration of these samples. We demonstrate that under specific environmental conditions, some sintered sugars may exhibit characteristics that enable their use as a proxy or analogue for various snow types in penetration testing.

## 2. Background

Blackford [5], in her review of ice, defined sintering as a thermal treatment for bonding particles into a coherent, predominantly solid structure via mass transport events that often occur on the atomic scale and Paterson [6] said that sintering of ice and snow is driven by the thermodynamical requirement to decrease surface energy, inducing an increase in both

density and strength. The initial stages involve the transformation of the snow ice crystals into a spherical form. Because the radius of an ice particle is larger than the concave radius of the bond joining it to an adjacent ice particle, there is a driving force to move mass to this concave neck area. Two previously spherical particles start tending towards a dumb-bell shaped particle joined by a neck; this bonding leads to improved strength and a lower energy system [7].

This process of mass distribution occurs throughout the sintering process. When this process occurs under additional pressure such as when snow is buried owing to accumulation, it is termed pressure sintering, and the rate of sintering is increased. Material densification results from the sintering process; however, Alley [8] clarifies that although numerous processes occur throughout the pressure sintering process, not all contribute to densification. Herron and Langway [9] identified three main phases in the densification process: settling and packing of particles, pore-space reduction, then pore-space closure. In snow, the densification process slows down in each stage, and also occurs intermittently throughout the year, depending on accumulation rates [10]. This process of intermittent densification was recently demonstrated by Einav and Guillard [11] using rice crispies and was previously described as self-organised criticality by Sammonds [12].

The primary mechanical observation to be drawn from this discussion is that the strength of snow is controlled by the size of the bonds formed between grains through sintering [13] and that the rate and amount of sintering occurs at different rates under varying environmental conditions.

The increase in snow strength attained over time can be assessed in various ways [14]. One of the most efficient means is penetration testing. Schneebeli [15] has extensively examined the strength of snow undergoing penetration with a micro-penetrometer and McCallum [16] has examined such behaviour using a friction-sleeve-equipped cone penetrometer. More recently, Peinke et al. [17] examined snow sintering at microscopic and macroscopic scales with high-resolution cone penetration tests. They showed that macroscopic penetration force increased over time due to microstructural bond strengthening.

In the absence of snow, other analogues have served as a proxy to describe the behaviour of snow under mechanical testing; these include:

- Sintered metal. Snow can be considered as a sintered material such as a metal, where, under stress, the usual fracture of the sintered necks takes place, as for most porous material [18]. This behaviour is consistent with the failure mechanism for snow described by Mellor [19].
- Geomaterials. Leroueil and Vaughan [20] showed that deposits normally treated as soils usually have characteristics due to bonded structure which are similar to those of porous weak rock, resulting in mechanically stiff behaviour followed by yield. They showed that such characteristics are common in natural geological materials and that it is the structure of weak rock and cemented sands that gives them their strength. This structure, arising from different causes, gives similar behaviour in many different materials including snow [20].
- Sedimentary material. Snow has historically been viewed specifically as a sedimentary material (Benson [21], Pielmeier and Schneebeli [22] and Schweizer et al. [23] amongst others) that ultimately may develop structure and thus behave in accordance with Leroueil and Vaughan's supposition [20] above.
- Porous Rock. Leite and Ferland [24], in their work on the indentation of porous material, note linear elasticity, yielding and structural collapse at a critical value, and strain hardening as the crushed material is compacted; all these behaviours are observed in the penetration of snow (of certain density). Tharp [25], in his work on polyphase rocks, suggests that incompetent phases (essentially non-load-bearing phases such as air) within a material result in the load-carrying framework behaving much like a porous solid, and snow has been considered as such by numerous authors including Brown [1], Kirchner et al. [4], and Petrovic [2].

- Foam. Snow has been specifically considered as a foam or a cellular solid by Brown [1], Kirchner et al. [4], Petrovic [2] and others including Johnson [3]. In his work on a statistical micromechanical theory for penetration in granular materials, Johnson [3] draws upon initial work presented by Gibson and Ashby [26], who examine the behaviour of foam under penetration in their review of the behaviour of cellular solids. Examination of Gibson and Ashby's work [26] suggests that below the pore close-off density of  $\sim 840 \text{ kg m}^{-3}$ , snow might be regarded as an open-cellular foam, whilst above this density, description as a closed-cellular foam may be appropriate.
- Polycrystalline ice. The main constituent of dry snow is ice, thus snow's behaviour must tend towards that of polycrystalline ice as density increases. Nicot [27] states that on the microscopic scale, the behaviour of grain bonds (within snow) is governed by the behaviour of ice, Gubler [28] describes the load-bearing capacity of snow in terms of ice chains, and Bartelt and von Moos [29] note the straining of the ice lattice within snow during triaxial testing. Graphs of stress versus strain rate generated by Kinoshita [30] through loading of snow are almost identical in form to those presented by Schulson [31] for polycrystalline ice.

Numerous analogues have been used successfully as a proxy for snow. We suggest that granular sugar may be a low-cost and readily available material that could be used to simulate the mechanical behaviour of snow.

### 3. Sugar as an Analogue for Snow?

Sugar is a synthesised organic material available in several shapes and sizes [32]. Raw sugars are refined and softened by removing the molasses coating through the process of affination [33]. The resulting syrup is then processed by precipitating and filtering solids in the syrup, then the liquor is spun using a centrifuge, separating the white crystals from the solution. These white crystals are dried in hot air and can then be used or packaged [34].

When stored in a sealed container, bonding between sugar grains is not evident [35]. However, when stored in a high humidity environment, sugar crystals bond; Bagster [36] speculated that these intergranular bonds form via crystalline bridging. Bagster [35] demonstrated an increase in raw sugar shear strength over time (out to  $\sim 100$  days), in a constant humidity environment. Zafar et al. [37] showed that sintering in a 'powder' such as sugar is influenced by time, temperature and moisture, and that increased bonding will result in an increase in material strength, similar to what is observed in dry snow.

We consider different sugar types (and grain sizes) as a proxy for different-sized snow grains, and we consider the variation in sintering over time, as for snow. Moreover, we consider the extent of sintering and the increase in strength for the sugars, at different humidity environments (at room temperature). This may serve as a proxy for different temperatures in snow sintering; because: the rate of sintering in snow, increases with greater temperatures [38], and the rate of sintering in sugar, increases with greater humidity [37].

### 4. Materials and Methods

Three types of refined sugar, of different grain size, raw, white and caster, were selected for testing; sugar densities were  $1237$ ,  $1367$  and  $1225 \text{ kg m}^{-3}$ , respectively. An amount of  $500 \text{ g}$  of each sugar type was used to determine a representative particle size distribution (sieve analysis); testing was conducted in accordance with AS 1289.3.6.1-2009. Three humidity environments were then established for each of five temporal periods in fifteen  $240 \text{ mm} \times 210 \text{ mm} \times 100 \text{ mm}$  plastic containers. Relative humidity (RH) within each container was established using particular types and quantities of saturated salt solutions, as described by Greenspan [39] (Table 1).

**Table 1.** Salt solutions used and corresponding relative humidity generated.

Salt Type	Water Content (ml)	Salt Content (g)	Humidity (%)
Magnesium chloride	20	100	33
Sodium chloride	75	100	75
Potassium sulphate	100	100	98

A small hole was drilled in the base of each container to enable insertion of temperature and humidity probe cables; these cables were connected to an Arduino UNO V2.0 Board and Expansion Board and then via USB to a PC.

Penetration testing of each sugar type, subjected to each of the three humidity environments, was envisaged after periods of 1, 5, 11, 18 and 25 days, and therefore 135 sugar samples were prepared in small aluminium dishes of diameter 80 mm and height 63 mm, and three samples of each sugar type were placed in each of the 15 plastic humidity containers. Aluminium dish dimensions were chosen to ensure that sufficient distance was maintained between the 22 mm diameter circular indenter and the dish boundary during penetration testing [26].

#### 4.1. Penetration Testing

Compressive loading via plates or indenters is the standard method for assessing the mechanical properties of snow (Wuori [40]; Abele [41,42]; Huang and Lee [43]; McCallum [44]; Peinke et al. [45]) and indentation tests have been used extensively in vehicle/snow interaction studies to obtain stress/displacement relationships (Jellinek [46]; Yong et al. [47]; Edens and Brown [48]; Shoop and Alger [49]).

A 10 kN Shimadzu AGS-X table-top universal test frame and manufactured cylindrical stainless-steel 22 mm diameter indenter was used to generate Force (N) versus displacement (mm) data for each sugar sample; these data were then converted to stress (kPa) and strain (%). Penetration rate was  $0.1 \text{ mm s}^{-1}$ ; penetration depth was limited to 20 mm. Three samples were tested for each sugar type (raw, white and caster), from each humidity environment (33, 75 and 98%) after a period of 1, 5, 11, 18 and 25 days, resulting in a total of 135 penetration tests; data were saved as .csv files.

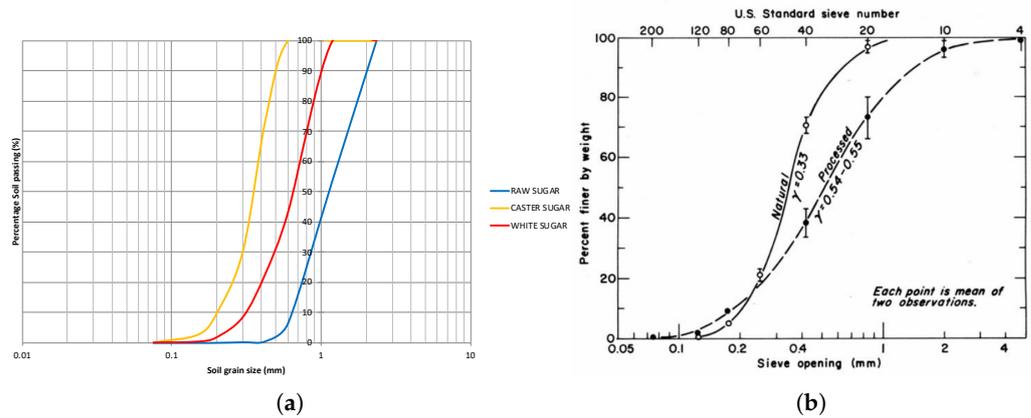
#### 4.2. Light Microscopy

During the 25 day testing period each sample was observed using an Olympus BX53M light microscope (Olympus Corporation, Shinjuku, Tokyo, Japan) to visually identify macroscopic sintering processes of grain necking, coarsening and densification. Olympus calibration software was used to align each sample under the scope and focused images were optimised for maximum contrast then saved as .jpeg files. Samples were observed for a short period of time (typically < 5 min) to minimise temperature/humidity variation.

## 5. Results and Discussion

### 5.1. Particle Size Distribution

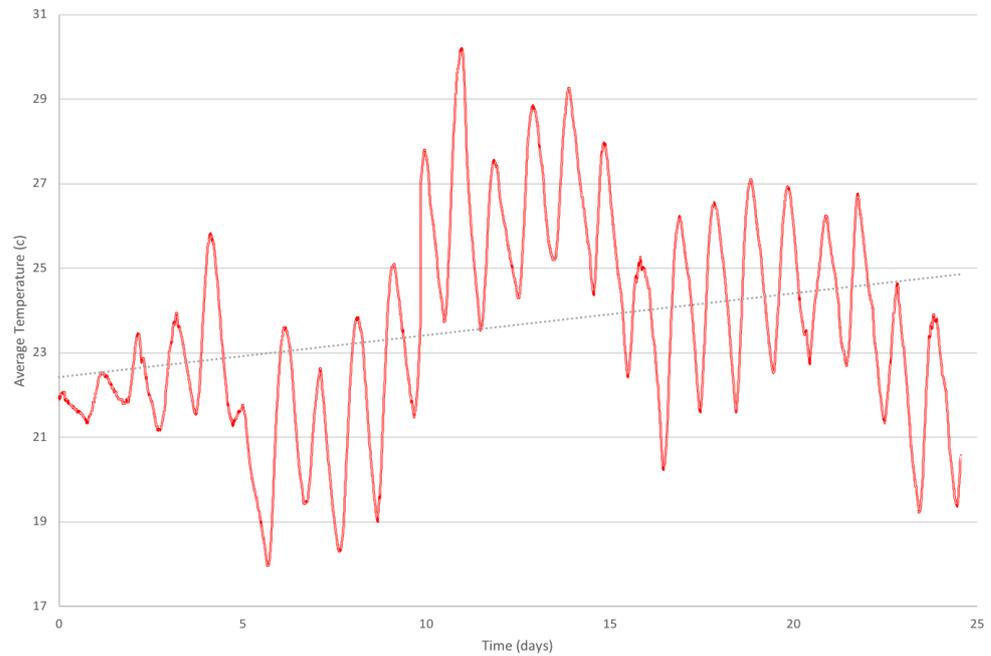
The particle size distribution for each sugar type is shown in Figure 1. These results suggest all samples were poorly graded or of consistent grain size. This is expected for manufactured sugar that has not experienced significant disturbance.



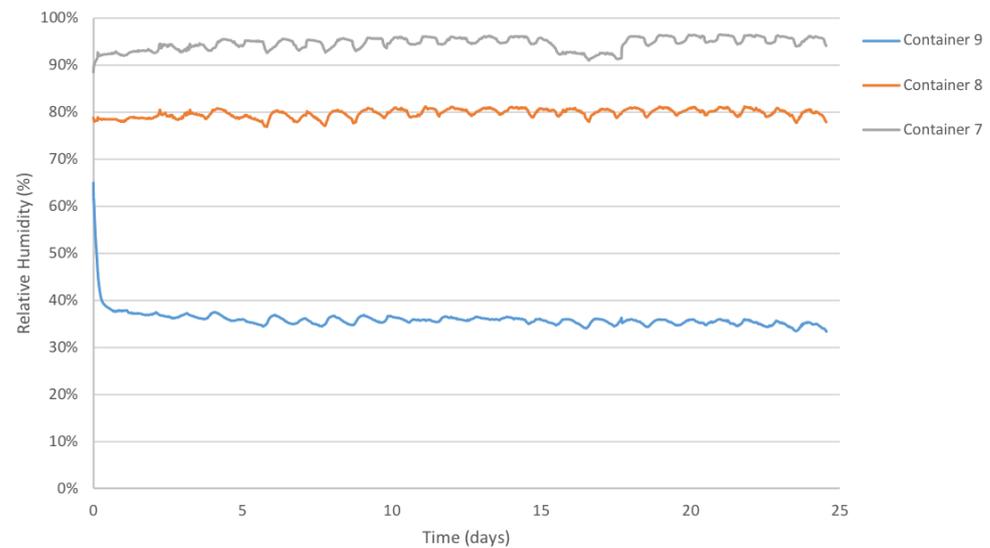
**Figure 1.** (a) Sieve analysis shows the variation in grain size between sugars and that all sugar types were poorly graded; compare with (b) typical particle size distribution for natural snow (density  $330 \text{ kg m}^{-3}$ ) and processed snow (density  $540\text{--}550 \text{ kg m}^{-3}$ ) (from Abele and Gow [50]).

5.2. Sample Temperature and Relative Humidity

Variation in temperature and relative humidity was monitored for containers 7, 8 and 9, containing potassium sulphate, sodium chloride and magnesium chloride, respectively, over the 25 day period prior to testing (Figures 2 and 3).



**Figure 2.** Average temperature readings across containers 7, 8, and 9, with linear temperature average trend line.



**Figure 3.** Average humidity readings for final containers throughout the 25 day testing period.

After equilibrium was reached, humidities were observed to remain largely constant and temperature was observed to vary with day-night variations; the average temperature over the 25 days was 23 °C. Average humidity recorded for each salt solution over the 25 day testing duration varied little from the theoretical relative humidities of 98%, 75% and 33%. Small variations (+/−5%) were evident; for example, container 9 (magnesium chloride) had an average RH of 36% over the 25 day duration, and container 7 (potassium sulphate) had an average RH of 95%. Container 8 (sodium chloride) exhibited the most variation, with an average reading of 80% RH.

### 5.3. Penetration Testing

Graphs of average stress (kPa) versus strain (%) are presented for each sugar sample at each relative humidity and elapsed time period; data shown are the average obtained from three tests (Figure 4a–i).

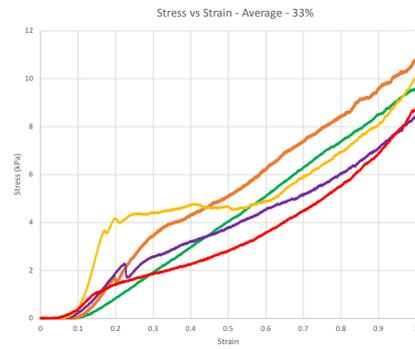
For sugars exposed to 33% humidity, the average strength of raw sugar was seen to increase the most; both white sugar and caster sugar showed little to no increase in average strength over the over the 25 day duration (Figure 5). Linear lines of best fit are shown.

For samples exposed to 75% humidity, caster sugar is observed to demonstrate the most significant increase in average strength over the testing duration. White sugar also increased in strength over time whilst raw sugar was observed to increase very little in strength over the 25 day period (Figure 6). Linear lines of best fit are shown.

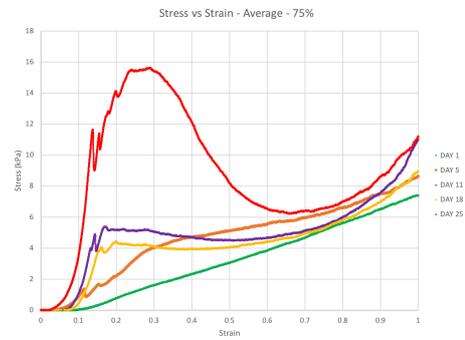
For samples exposed to 98% humidity, a general increase in strength is identified across all sugar types, with white sugar demonstrating the greatest increase. Caster sugar experienced the second greatest increase in strength whilst raw sugar experienced the least (Figure 7). Linear lines of best fit are shown.

The trends evident across all observations are that as sintering time increases, resistance to penetration also increases; this is consistent with Colbeck’s observation in snow Colbeck [13] and is consistent with Bagster [35]. It is also generally evident that as environmental humidity increases, absolute strength increases, presumably because the size of the sintered bonds between sample particles increases. This is broadly consistent with Bagster’s observations of raw sugar using an electron-microscope and optical means [35] and is consistent with [37]. What is intriguing is the variation exhibited by raw sugar: significant strength increase is observed over time at RHs of both 33% and 98%. However, negligible strength increase is evident at 75% RH. We are unable to explain this discrepancy at this time.

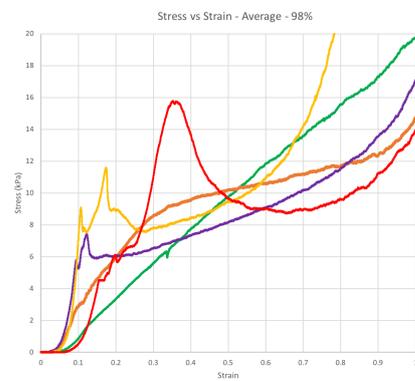
In snow, strength increase with time can often be described using a power-law relationship; for example, Peinke et al. [17] and Abele [41] observed an exponential increase; but, this is not evident in our data from sugar.



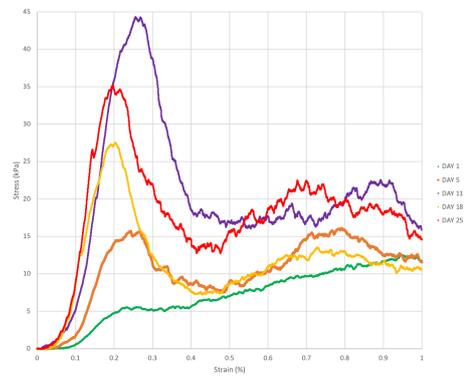
(a) Caster sugar at 33% RH.



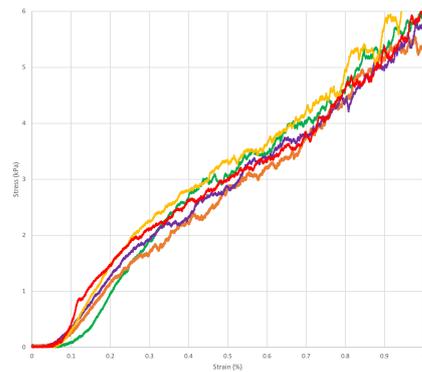
(b) Caster sugar at 75% RH.



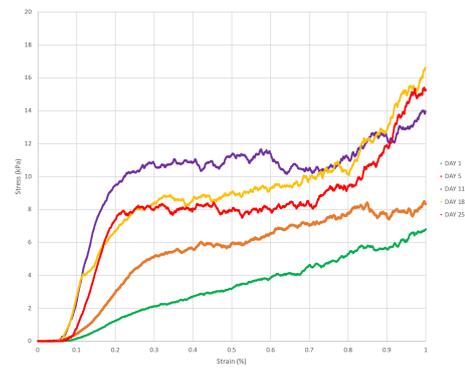
(c) Caster sugar at 98% RH.



(d) Raw sugar at 33% RH.

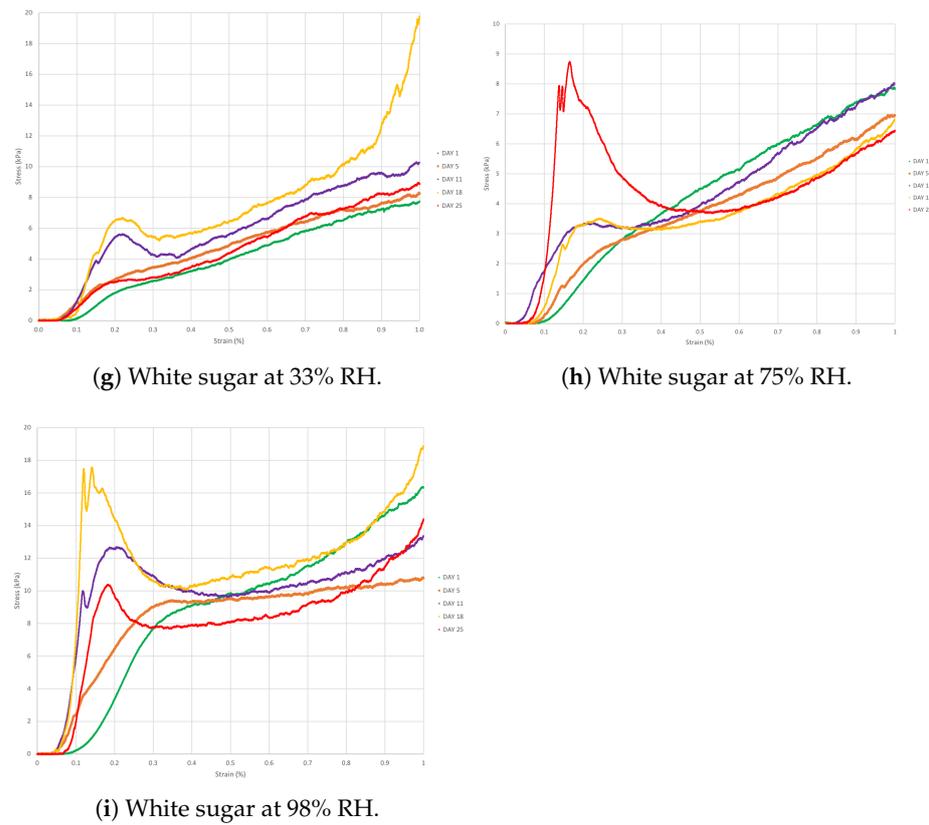


(e) Raw sugar at 75% RH.

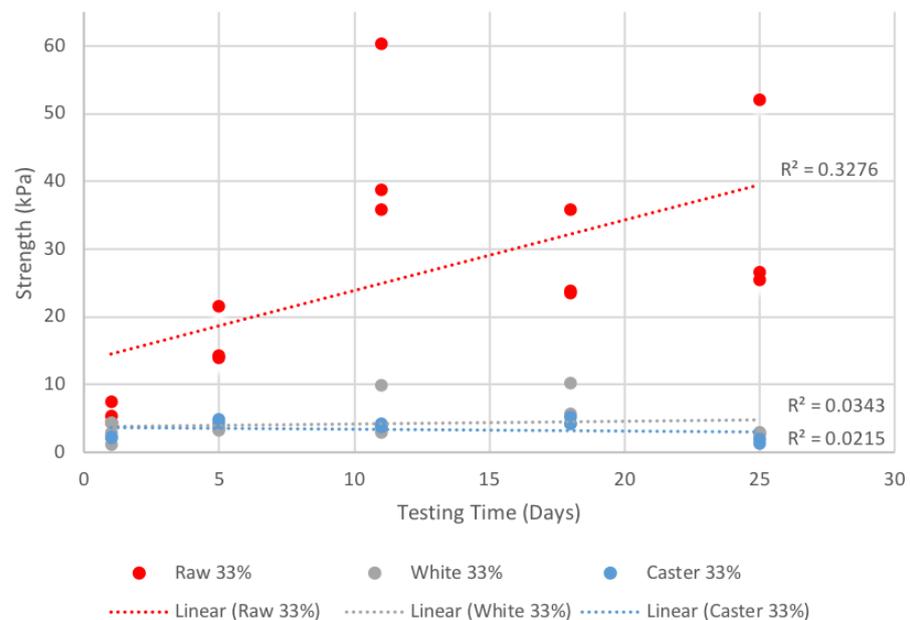


(f) Raw sugar at 98% RH.

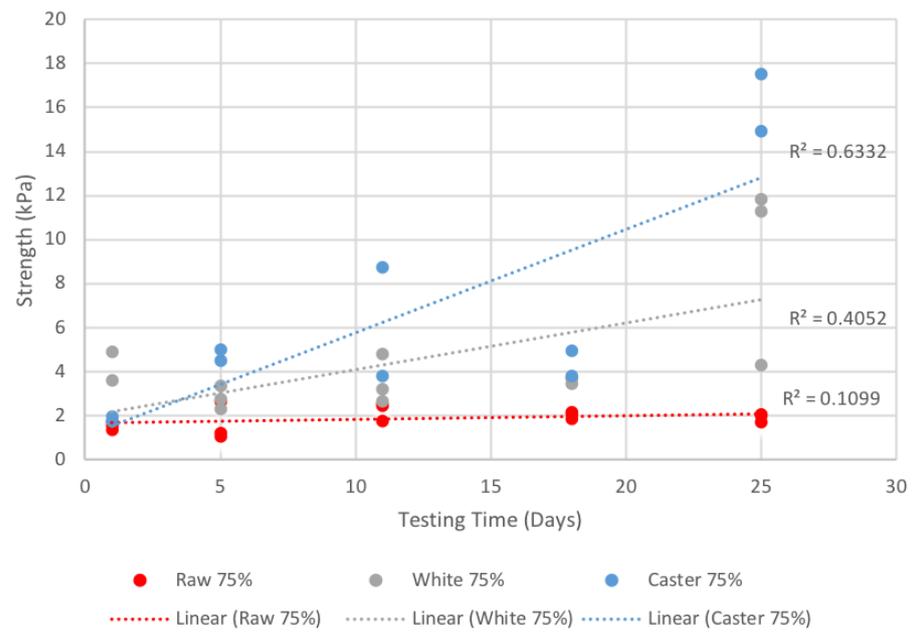
Figure 4. Cont.



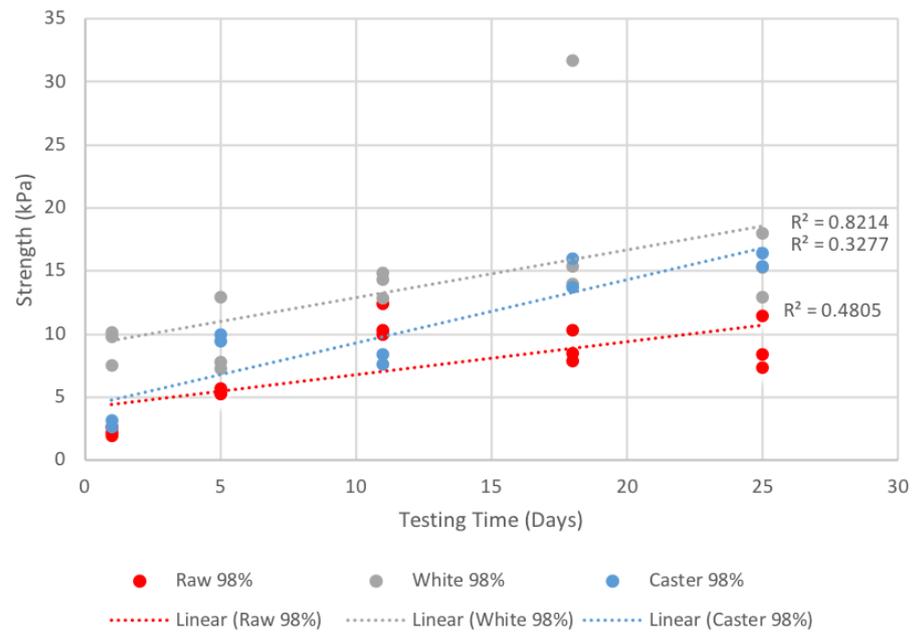
**Figure 4.** Average stress vs. strain for all sugars at each humidity at all assessed temporal periods. (a). Caster sugar at 33% relative humidity, (b). Caster sugar at 75% relative humidity, (c). Caster sugar at 98% relative humidity, (d). Raw sugar at 33% relative humidity, (e). Raw sugar at 75% relative humidity, (f). Raw sugar at 98% relative humidity, (g). White sugar at 33% relative humidity, (h). White sugar at 75% relative humidity, (i). White sugar at 98% relative humidity.



**Figure 5.** Temporal variation in strength for all sugars sintered at 33% RH. Note: vertical axis differs to Figures 6 and 7.



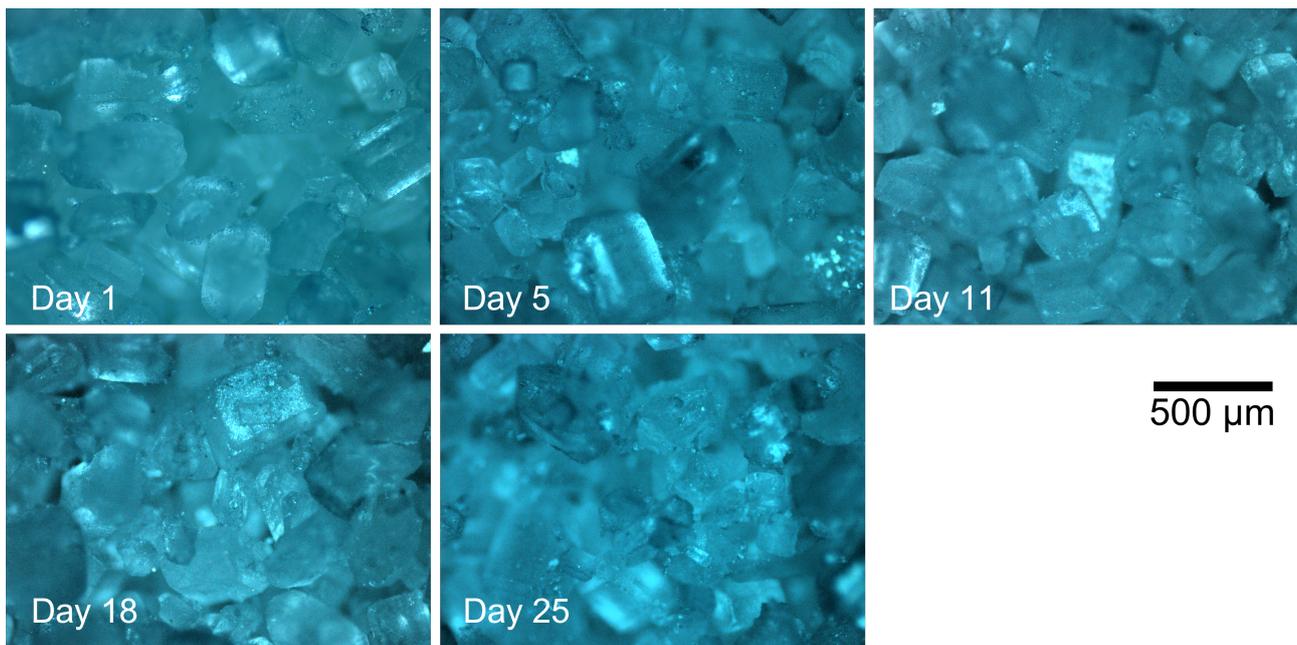
**Figure 6.** Temporal variation in strength for all sugars sintered at 75% RH. Note: vertical axis differs to Figures 5 and 7.



**Figure 7.** Temporal variation in strength for all sugars sintered at 98% RH. Note: vertical axis differs to Figures 5 and 6.

5.4. Visual Observations from Light Microscopy

Images from light microscopy of caster sugar show increased sintering over time (Figure 8; caster sugar at 33% RH). Images for remaining sugars and humidities are available upon request.



**Figure 8.** Light microscopy images of caster sugar samples over a 25 day period at 33% relative humidity.

Little to no structural change is observed from the light microscopy samples obtained at 33% RH; this is consistent with mechanical strength data that show little to no increase in strength over 25 days. Bagster [35] observed no strength increase in raw sugar after about six weeks (loaded under 15.2 kPa; humidity unknown). Raw sugar samples display a small amount of coarsening and some bonding between particles is apparent.

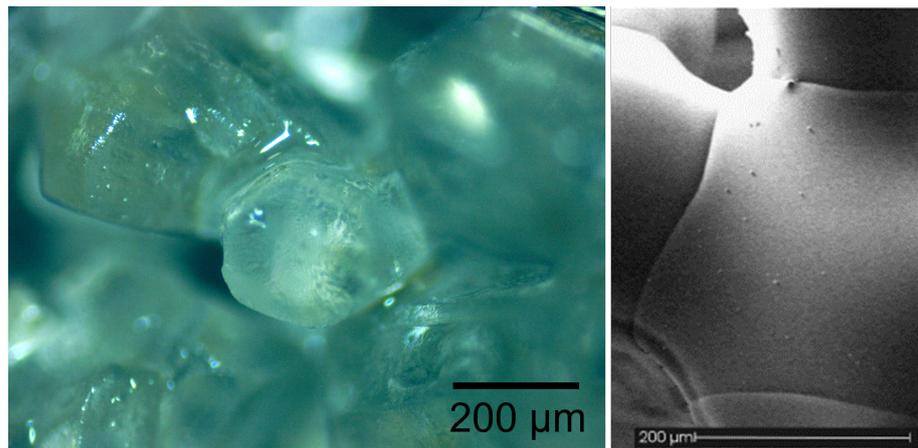
For samples exposed to 75% RH, coarsening and some particle bonding and pore shrinkage associated with early stage sintering were evident in the smaller-grained caster and white sugars, compared to the coarser raw sugar. These observations are consistent with the penetration tests that illustrate an increase in strength in both caster and white sugar.

Macroscopic sintering was evident in all samples exposed to the 98% RH salt solution. Small sintering necks were evident between particles in all samples through days 1–5 with pore shrinkage and grain coarsening evident between 5 and 18 days. Coarsening remains evident in raw sugar at day 25, whereas both smaller-grained sugars show evidence of complete pore disappearance after this time. These observations are consistent with penetration test data where both caster and white sugar at 98% RH illustrate greater strength properties than raw sugar.

##### 5.5. Comparisons with Snow

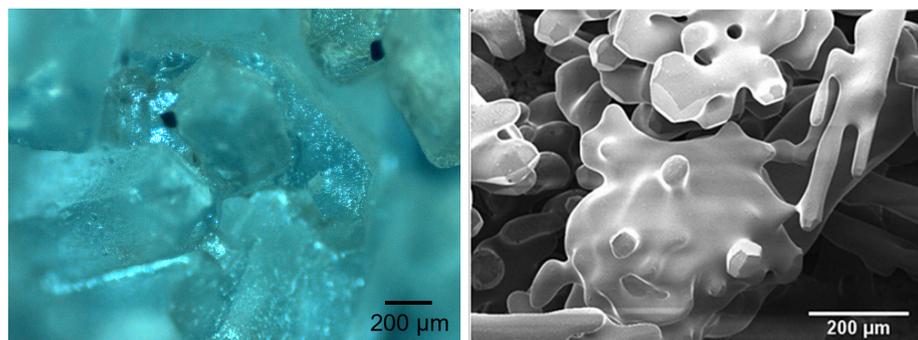
Particle size distributions (PSDs) for both natural and processed snow are very similar in shape and absolute magnitude to the PSDs for the three types of sugar (Figure 1), with natural snow and caster sugar particularly showing similar distribution between sizes of 0.1 mm and 1 mm.

Comparison of light microscopy images shows that the initial stages of necking within raw sugar exposed to 98% RH after 1 day is similar to necking observed in sintered snow (Figure 9).



**Figure 9.** Grain necking in raw sugar after one day compared to necking in snow crystals after eight days (reproduced from Barnes [51], with the permission of AIP Publishing).

Although shapes differ, similar necking boundaries are evident. Similarities in macroscopic grain coarsening are also observed between sugar and snow crystals (Figure 10).



**Figure 10.** Comparison of raw sugar crystal coalescing and 3D scanned FHT snow coalescing (from Wang and Baker [52]).

Hardness or resistance obtained via penetration is accepted to be equivalent to the compressive strength of snow [53]. Herein, sugar strengths determined through penetration testing are similar to the strength ( $\sim 4$  kPa) exhibited by unprocessed snow subjected to uniaxial compression [54]; this strength is comparable to that observed in sugar subjected to the following conditions:

- Raw sugar at 33% RH after 1 day,
- White sugar at 75% RH after 11–18 days,
- Caster sugar at 75% RH after 5–18 days, and
- Raw sugar at 98% RH after 5 days.

Wang and Baker [52] also examined strength variation in unprocessed natural snow of various densities. Representative strengths for sintered low-temperature (SLT) and fresh high-temperature (FHT) snow are similar to the strength observed for raw sugar at 33% after 18–25 days (20–30 kPa) and representative strengths for FHT-1 and FHT-2 (20 kPa) are comparable to those observed in sugar subjected to the following conditions:

- Caster sugar at 75% RH after 25 days,
- Caster sugar at 98% RH after 25 days, and
- White sugar at 98% RH after 18 days.

Mede et al. [55] also present natural snow compressive strengths similar to strengths determined from the sugar samples. Peak strength observed from all sugar penetration tests was for raw sugar at 33% RH after 25 days (60 kPa). This strength is similar to that

observed in sintered snow at  $-49\text{ }^{\circ}\text{C}$  after 1–10 days undergoing unconfined compression testing ( $\sim 50$  to  $100\text{ kPa}$ ) [14].

Most snow strengths determined by Wang and Baker [52] (up to  $\sim 45\text{ kPa}$ ) are an order of magnitude greater than those we observed in sugar ( $\sim 5\text{ kPa}$ ), but some sugar strengths (raw sugar at 33%; see Figure 4) did exceed  $50\text{ kPa}$ . These preliminary observations and comparisons suggest that particular sugar types after specific sintering periods at particular humidities, may be useful as an analogue for snow undergoing penetration testing under specific environmental conditions.

## 6. Conclusions

In this study, we briefly examined whether sintered sugar can be used as an analogue for snow in penetration testing. Through direct light microscopy observations, we determined that sugar is seen to illustrate similar macroscopic sintering processes to snow; and via penetration testing, we determined that sugar sintered within various relative humidity environments gains increased strength over time, demonstrating strengths similar to that observed within low-density unprocessed natural snow. Testing over the temporal periods described herein suggests that sugar may need to sinter for a greater period of time to realise strengths typically evident in sintered snow. However, in the absence of cold-room testing facilities, it appears that sugar may serve as a useful proxy for snow both qualitatively and quantitatively, over a range of different material types, humidities and sintering durations. Although no sugars were seen to share similar characteristics to processed snow at higher temperatures, these characteristics may be equivalent to conditions experienced by natural snow in cold polar environments.

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