

Article

Evaluating Snow Pavement Strength in Remote Cold Environments via California Bearing Ratio (CBR) and Russian Snow Penetrometer (RSP) Combined Testing

Katie L. Duggan DiDominic ^{1,*} , Margarita Ordaz ², Terry D. Melendy, Jr. ¹  and Chrestien M. Charlebois ¹

¹ US Army Engineer Research and Development Center Cold Regions Research and Engineering Laboratory (ERDC-CRREL), Hanover, NH 03755, USA; terry.d.melendy@usace.army.mil (T.D.M.J.); chrestien.m.charlebois@usace.army.mil (C.M.C.)

² US Army Engineer Research and Development Center Geotechnical and Structures Laboratory (ERDC-GSL), Vicksburg, MS 39180, USA; margarita.ordaz@usace.army.mil

* Correspondence: katie.l.didominic@usace.army.mil; Tel.: +1-(603)-646-4601

Abstract

Accurate assessment of compacted snow strength is critical for ensuring the safety and performance of snow runways in cold environments. The Russian Snow Penetrometer (RSP) is widely used in snow science and engineering due to its simplicity, portability, and capability for rapid field measurements under extreme conditions. Conversely, the California Bearing Ratio (CBR) test remains the benchmark for evaluating the load-bearing capacity of conventional granular materials but is seldom applied to snow because of logistical constraints and the material's complex mechanical behavior. The relationship between these two pavement evaluation tools remains poorly defined. This work investigates how RSP strength indices relate to CBR measurements to determine whether the RSP can serve as a practical proxy for snow pavement load-bearing capacity. Side-by-side field measurements of snow pavement strength were collected over a 30 h period at two test section locations. Both methods captured temporal strength increases and spatial variability, with consistently higher values at the second site attributed to extended sintering. A moderate linear correlation ($R^2 = 0.44$) between RSP and CBR results supports a quantifiable relationship between the two methods. These findings begin to bridge the gap between conventional pavement testing and snow-specific strength evaluation, demonstrating the potential of the RSP for rapid assessment of snow runways. Continued data collection and analysis will refine this relationship and strengthen its applicability for operational use.

Keywords: snow pavement; load-bearing capacity; Russian Snow Penetrometer; California Bearing Ratio; compacted snow runway; snow strength



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1. Introduction

In cold regions and expeditionary engineering, accurately evaluating the strength of compacted snow surfaces is critical for the safe and effective operation of roads, airfields, and construction pads/foundations. Snow pavements, though unconventional, are often used to support logistical and military operations in remote cold environments, where traditional infrastructure is unavailable or impractical [1,2]. In such scenarios, a rapid, field-based strength assessment method to ensure sufficient load-bearing capacity is essential, particularly for aircraft operations where surface failure poses a significant safety risk [3,4].

The California Bearing Ratio (CBR) test has long been recognized as the gold standard for assessing the strength and load-bearing capacity of soils and unbound pavement layers [5]. Field CBR testing, which measures material response in situ, is widely valued for its realistic representation of actual performance. However, despite its reliability, field CBR testing is slow, labor-intensive, and logistically complex, especially in remote extreme environments [6]. Field CBR procedures are well established through standards such as CRD-C 654 and ASTM D4429, which provide consistent methods for evaluating in situ strength of soils and unbound pavement layers [7,8]. However, these standards were developed for conventional geomaterials, and no equivalent framework exists for snow pavements, resulting in limited guidance for interpreting CBR values in cold-region applications. The CBR test is highly sensitive to moisture content, with soaked specimens typically showing significantly lower strength values compared to dry ones [9]. This sensitivity, while well-understood in soil engineering, presents unique challenges when applying the CBR test to snow. Snow's highly variable moisture content, which is impacted by factors such as temperature, density, and metamorphic state, can introduce variability in CBR measurements. This variability highlights the need to establish typical CBR values for different snowpacks. Snow pavements may have CBR values much lower than granular materials, but this does not necessarily indicate weaker strength or a reduced ability to support loads. Rather, it may suggest that snow operates within a different range of CBR values, which requires further investigation to understand its performance characteristics under load. As a result, very limited CBR data exists for snow, limiting our understanding of how this test applies to snow pavement systems. Although snow strength has been examined extensively in cold-regions engineering, particularly with penetrometers and bearing tests, few studies have directly measured CBR on snow [6]. Existing investigations have focused primarily on snow compaction behavior, load-support capacity, and metamorphism, leaving a gap in standardized evaluation of snow pavements using pavement-design metrics such as CBR [6,10].

The Dynamic Cone Penetrometer (DCP) is a simpler, faster, and more portable tool. Originally intended as an index test, the DCP measures penetration resistance and can be empirically correlated to CBR values [10]. While DCP-based CBR estimates are routinely used in soil engineering [11,12], several studies have extended this approach to frozen ground and snow, albeit with limited standardization [13–15]. Still, both CBR and DCP were developed for conventional granular materials, not snow. Snow behaves very differently in that its strength characteristics vary significantly with temperature, density, moisture content, and metamorphic state [2,16,17]. These properties make it difficult to apply soil-based correlations with confidence. Even when processed and compacted under controlled conditions, snow roads and airfields fail under traffic loads differently than typical road or airfield construction materials, challenging the applicability of standard interpretation protocols. Therefore, CBR values derived from snow may not correlate at all with traffic-bearing capabilities of conventional pavements, even when measured using accepted standards.

In recognition of these challenges, researchers and military engineers use an alternate method more suited to extreme cold environments. The Russian Snow Penetrometer (RSP) has become the primary field instrument for assessing snow strength due to its portability, mechanical simplicity, and long history of successful use in polar field programs [18]. The RSP is a hand-driven device that, like the DCP, measures the resistance of snow to penetration. The RSP is simple, rugged, and field-proven under Arctic and Antarctic conditions. Similar to DCP, it requires no hydraulic or electronic components, making it mechanically consistent and reliable in extreme cold environments where snow pavements exist. Although RSP and DCP operate on similar principles, and qualitative comparisons

suggest that they track similar trends in snow strength [18], no direct, validated conversion currently exists between RSP and CBR values. In practice, RSP results are sometimes converted to estimated CBR values via a two-step empirical process: first converting RSP readings to equivalent DCP penetration rates (mm/blow) [18], then estimating CBR from DCP via traditional correlations [12,19,20]. This approach is convenient but introduces compounded uncertainty due to assumptions in each step, especially given that DCP-CBR correlations were developed for soil, not snow. This lack of a direct, validated RSP-to-CBR relationship presents a critical gap. In operational environments where snow pavements must support aircraft or heavy loads, reliable strength indices are essential for safety, design, and maintenance decisions. Yet current methods are either impractical in the field (i.e., CBR), only approximate (i.e., DCP-based estimation), or are not easily compared to accepted standards for granular material (i.e., RSP).

The objective of this study is to address a critical gap in the current understanding and application of pavement strength evaluation methods for compacted snow surfaces. While existing tools like CBR and RSP are individually recognized for their utility in soil and snow pavement evaluation, there has been no validated correlation between the two, creating significant uncertainty in comparing their results. The innovation of this research lies in directly correlating RSP measurements with field CBR values, providing a clearer understanding of how these two methods can be used together to assess snow pavement strength. This approach eliminates the need for intermediate and error-prone steps, such as DCP-based conversions, and directly compares two well-established field tests in the context of snow pavements. Furthermore, this work contributes to the development of a practical framework for rapidly assessing snow pavements in operational settings, with significant implications for military and expeditionary engineering where snow-runway performance is critical. By generating paired data from both tests under realistic snow conditions, this study not only advances the scientific understanding of snow pavement strength but also has the potential to improve field testing protocols for infrastructure in cold regions.

2. Materials and Methods

2.1. Construction of Snow Runway Test Section

To establish a reliable relationship between RSP and CBR, a full-scale snow runway test section was constructed in the Cold Regions Research and Engineering Laboratory (CRREL) Frost Effect Research Facility (FERF) in Hanover, NH. Construction of the snow runway test section began by placing stockpiled snow that had been collected from naturally occurring, undisturbed snow previously accumulated at CRREL. The natural snow's individual grains ranged from approximately 2–3.5 mm. Stockpiled snow was used rather than freshly fallen snow, which is a common practice in controlled snow pavement and snow mechanics experiments. Prior studies have shown that reprocessed stockpiled snow (typically through blowing, milling, or mechanical breakup) has an accelerated rate of grain growth and bond formation because of the disaggregation and after such reprocessing, the mechanical behavior of snow is again governed primarily by density, temperature, and compaction effort rather than its storage history [13]. In this study, the snow was fully reprocessed through a snowblower prior to placement, which breaks down cohesive clumps and reduces layering effects, thereby minimizing any residual influence of stockpiling on the resulting compacted snow pavement. The collected snow was processed using a skid steer (Caterpillar 299D3 Compact Track Loader, Irving, TX, USA) outfitted with a snowblower attachment (Caterpillar SR321, Irving, TX, USA) and placed within the designated testing area. After processing/disaggregation with the snowblower, there was a more homogenous snow matrix with consistent grain size and moisture distribution

(i.e., snow grains were 1 mm on average), establishing more uniform initial conditions for sintering following compaction and curing time. The snow was placed in successive lifts of 15.24 cm. Between each lift and prior to compaction, a rake was used to manually smooth any smaller uneven areas. Each lift was compacted using a vibratory plate compactor (Wacker Neuson WP1550AW, Munich, Germany), with three compaction passes applied per lift to ensure adequate densification. This process was repeated for a total of three lifts, resulting in a constructed snow pavement section approximately 0.45 m thick. To achieve a smooth final surface, plywood sheets were laid side by side across the top layer and a skid steer was driven over them to level and consolidate the surface. Although there was noticeable contamination from wood chips eroded from the trafficking, testing with both field CBR and RSP were conducted on uncontaminated snow surfaces.

During construction, the temperature of the FERF was approximately -5°C , but was maintained at approximately -7°C for the duration of the study (i.e., during all CBR and RSP testing). Although humidity was not measured during this study, data from a similar testing period in the previous year at the same temperature indicate that relative humidity in the FERF averaged 85.2%. The FERF also generally gets drier throughout the winter season as the refrigeration system pulls out moisture. This provides context for the moisture conditions expected during the testing period. The snow was compacted under frozen conditions, and no significant moisture fluctuations were observed during testing. However, as snow compacts and sinters over time, the internal structure of the snow can change, which may slightly affect how moisture is distributed within the snowpack. This can result in small variations in snow strength at different points along the test section. The constructed snow pavement test section was 12.2 m long and 6.3 m wide (Figure 1). CBR and RSP tests were conducted at STA 1 and STA 2 along the centerline (C/L) of the test section sequentially to monitor snow strength gain within a 30 h period after initial construction. The snow runway was first tested 12 h after final construction to allow sufficient hardening to support the CBR test vehicle. This initial test is referred to as Test 0 and serves as the baseline condition for the snow pavement. Due to the inherently lengthy and labor-intensive nature of field CBR testing, as many tests were conducted as possible within the first 30 h following Test 0. This resulted in CBR and RSP testing at five total time durations (Table 1). The time intervals between replicate tests were naturally dictated by operational considerations such as the pace of test setup, running the CBR test itself, the speed of equipment relocation for each replicate, and analysis of error rates between replicates. Early tests (i.e., Test 0 and Test 1) were spaced close to initial construction (i.e., within the first 24 h) to capture initial hardening behavior, while later tests (i.e., Test 2, Test 3, and Test 4) outside the first 24 h were included to capture longer-term strength gain. The larger gap between the earlier tests reflects these initial logistical challenges; as the testing progressed, increased efficiency allowed for shorter intervals between subsequent measurements. This testing schedule was chosen to capture early-stage strength development following compaction, which is the period of most rapid hardening and is operationally critical for snow pavements supporting aircraft or heavy loads. To isolate the effect of snow properties on strength, the FERF temperature was held constant throughout the experiment, removing temperature fluctuations as an additional variable while establishing baseline CBR values and comparing them to RSP measurements. While later strength gains may continue beyond the 30 h window studied here, previous work indicates that the majority of load-bearing capacity is achieved within the first 24–48 h under similar compaction conditions [10,18]. Future studies could examine longer-term trends and the influence of variable temperature regimes.

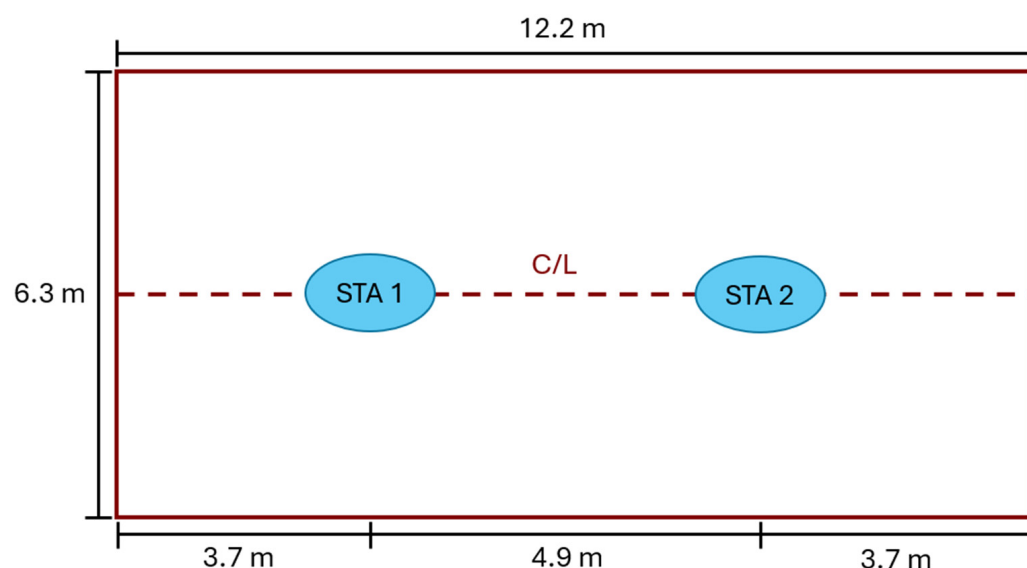


Figure 1. Compacted snow pavement test section schematic showing the two locations where CBR and RSP strength measurements were collected (i.e., STA 1 and STA 2).

Table 1. Time points for CBR and RSP strength measurement collection. The snow pavement test section was allowed to harden overnight (i.e., approximately 12 h) prior to Test 0, but this is considered “time 0” and is therefore referred to as initial snow placement.

Test Number	Time
Test 0	Initial Snow Placement
Test 1	6 h post-construction
Test 2	23 h post-construction
Test 3	27 h post-construction
Test 4	30 h post-construction

2.2. Snow Pavement Test Methods

2.2.1. California Bearing Ratio (CBR)

CBR testing is selected for this purpose because it is the recognized gold standard in pavement subgrade strength evaluation. Despite the unconventional nature of snow as a pavement material, adapting field CBR procedures allows for consistency with military and civil pavement design practices. The use of CBR on snow provides a basis for performance comparison, design validation, and decision-making aligned with established engineering frameworks [6]. Field CBR testing was performed in accordance with CRD-C 654 [7]. The field test is especially useful for variable or layered materials where laboratory remolding would not capture natural structure or in-place density [8]. Tests 0–1 were performed using CRREL’s CBR kit, while Tests 2–4 employed a kit from the Geotechnical and Structures Laboratory (GSL). GSL’s kit was more streamlined, but did not arrive from Vicksburg, MS until testing had already begun, hence starting with the kit available at CRREL. Both kits adhered to the required standard and yielded comparable CBR results, though differences in apparatus configuration and handling were noted. CRD-C 654 specifies procedures for evaluating in situ material strength using a static load applied through a circular piston. The standard setup consists of a load frame, a vehicle-mounted reaction beam system, a calibrated proving ring to measure applied force, and dial gauges to record piston penetration [7]. Although the CRREL and GSL CBR kits differ slightly in frame configuration and handling, both employ the same standardized penetration piston, seating load, loading rate, and calibration requirements. During testing, the transition between kits did not produce any discontinuities in measured CBR values, and the results followed

a consistent strength-development trend across all tests. These observations support the functional comparability of the two devices. However, we note that a formal side-by-side comparison was not feasible due to the FERF refrigeration season ending and therefore lack of time to keep the snow pavement test section cold enough for additional testing (and testing that was not initially planned for). We recommend such a comparison in future work to quantitatively assess potential systematic differences between multiple CBR test kits.

Since snow pavement strength was expected to be low at the start of testing, the CBR equipment was mounted to a four-wheel drive truck to ensure successful navigation to the test location. To further mitigate the risk of the truck becoming immobilized or causing rutting on the test section, wooden platforms were strategically placed along the wheel paths to distribute loads and improve traction over the snow surface to each test location (i.e., STA 1 and STA 2). The required reaction load (i.e., weight to be added to the bed of the truck) for field CBR testing is determined based on the maximum penetration resistance expected during the test. The reaction load must counteract the maximum penetration resistance during testing. Estimated CBR values based on DCP correlation for snow range from 0 to 20 [13–15]. Therefore, a target CBR of 30 was used to calculate the expected reaction load. Since CBR is the ratio of the measured load to the standard load (i.e., 1360.8 kg for 2.5 mm penetration and 2041.2 kg for 5.0 mm penetration) [8], the measured load (in this case, the reaction load) can be obtained using $\text{CBR} = 30$ and a maximum standard load of 2041.2 kg. This indicated a required reaction load of at least 612.3 kg. Large concrete ballast was placed in the bed of the truck to achieve this reaction load. After preparing the CBR truck with the appropriate reaction load, the CBR test beam was mounted to the vehicle hitch. The beam was supported on both ends by jacks to stabilize the beam and distribute reaction loads. The jacks rested on base platforms to prevent jack settlement in the snow (Figure 2). A level was used to ensure the CBR apparatus was level in both horizontal and vertical directions.



Figure 2. Field CBR setup including the truck with reaction load in the bed, CBR beam, piston apparatus, jacks, base platforms, and plywood sheets used to avoid localized surface disturbance/rutting from the truck tires.

The CBR test configuration used in this study featured a 76.2 mm diameter penetration piston (the standard size prescribed by CRD-C 654) that was responsible for applying vertical load into the snow surface to assess resistance and determine the bearing ratio. Load measurements were captured using a calibrated proving ring mounted in line with the piston to monitor real-time applied force. Two dial gauges were employed: one to measure deflection in the proving ring and the other to record piston penetration. All components, including the piston, proving ring, and dial gauges, were mounted in precise alignment on a rigid support frame to minimize system deflection, ensure accurate load transfer into the snow pavement, and maintain the integrity of the load–penetration relationship. A standard surcharge plate and associated weights were also used to simulate overburden pressure from the material that will overlie the layer being evaluated. The surcharge plate measured 152 mm in diameter with a thickness of 7.6 mm. A 4.5 kg surcharge weight was applied concentrically to reflect realistic in-service loading conditions.

Following surcharge placement, the penetration test was initiated by advancing the piston into the snow at a controlled rate of 1.3 mm per minute. Load was applied using a mechanical actuator, and resistance was continuously recorded using a calibrated proving ring and dual dial gauges. Load and displacement readings were taken at 0.64 mm intervals up to a maximum penetration depth of 12.7 mm unless a peak load was reached earlier. These data were used to construct a load–penetration curve, from which the CBR value was calculated as the ratio of measured pressure to a standard reference pressure at 2.5 mm or 5.0 mm of penetration, whichever resulted in a higher value. The higher the CBR value (i.e., between 0 and 100), the stronger the material. The three most closely related CBR values per station location were used to conduct the data analysis based on CRD-C 654 guidance which requires re-testing in cases of high variability among replicates. CBR data were processed per CRD-C 654 guidelines then analyzed and visualized using Excel.

2.2.2. Russian Snow Penetrometer (RSP)

The RSP is a well-established method for evaluating snow strength in extreme cold environments [10,18]. The RSP is a dynamic, point-based instrument designed to evaluate the mechanical strength of highly compacted snow and glacial ice surfaces, such as those found on polar airfields. It operates by measuring the resistance of the snow or ice to penetration by a conical tip under repeated impacts from a controlled mass dropped from a fixed height. The RSP shares a similar operational principle with other penetrometers such as the DCP and the Rammsonde penetrometer described earlier, which vary in their drop mass, cone geometry, and target application. While the RSP is optimized for highly compacted snow and ice, the DCP is better suited for evaluating sub-surface layers below pavement, and the Rammsonde penetrometer is ideal for lower-strength snow on natural or less compacted surfaces. While the Rammsonde can be affected by the timing between successive drops due to minor frictional heating effects, which in some cases may allow small ice lenses to form and artificially increase measured resistance during longer pauses, such effects are not observed or are negligible with the RSP. The RSP is used for very dense snow, and common applications tend to be under colder and drier conditions on compacted snow and ice surfaces, where frictional heating is minimal and has no measurable influence on recorded strength. As such, hammer drops were applied at a consistent, natural pace without intentional delays to account for this. The RSP used in this study was produced in-house at the CRREL machine shop. It consists of a slender vertical rod equipped with a 30-degree conical tip having a maximum diameter of 11.5 mm. A 1.75 kg drop hammer is repeatedly released from a drop height of 50 cm, driving the tip into the snow or ice surface to a maximum penetration depth of 400 mm (Figure 3). For each drop, the depth of

penetration is recorded, and the total number of drops required to reach a certain depth can be used to infer snow strength (i.e., RSP index with units of kg) (Equation (1)).



Figure 3. A researcher performing the RSP method for measuring the strength of the compacted snow pavement test section prior to the corresponding CBR measurement.

Calculating strength with RSP test data:

$$\text{RSP Index} = \left(\frac{W \times h \times n}{L} \right) + W + Q \quad (1)$$

W is the mass of the drop hammer (kg), h is the height from which the weight was dropped (cm), n is the number of hammer drops or “blows”, L is the penetration depth (read from the markings on the rod) after n blows (cm), and Q is the mass of the penetrometer itself (kg) [10,21]. DCP tests are conducted identically, however a “fixed” number of blows is applied, and the resulting penetration is recorded, resulting in an index value with units of distance per blow. This method provides a rapid, repeatable means of characterizing snow strength at specific points along a runway or test site. As for DCP, because the measurements are localized, adequate spatial coverage is essential to develop a representative assessment of overall runway strength.

To achieve approximately side-by-side measurements of CBR and RSP, the RSP measurements were collected immediately prior to each CBR replicate at the same station. While the CBR apparatus needed to be temporarily moved to allow RSP testing, resulting in a short time lag between the two measurements, this approach minimized spatiotemporal inconsistencies and ensured that both tests sampled nearly the same location and depth. RSP measurements were taken in triplicate for each CBR replicate. To the maximum extent practicable, the three RSP replicate measurements were positioned evenly around the center of the planned CBR collection point to achieve a representative average of the localized area.

In general, the three test points formed an evenly spaced triangle placed approximately at the edge of where the CBR surcharge plate was to be positioned. One person performed the RSP test as described above while another recorded the number of hammer blows and resulting depth of penetration. The starting penetration depth ranged from 0 to 25 mm depending on the level of surface disturbance from personnel and equipment traffic prior to testing.

Following the experiment in the FERF, the collected RSP and CBR data were imported into R Statistical Software (R Foundation, Vienna, Austria) for in-depth analysis, processing, and visualization and to perform the correlation analysis between CBR and RSP [22]. The ‘tidyverse’ package was used for all processing, analysis, and visualization [23]. RSP data was plotted in R to visualize strength index across depth for each RSP replicate. The RSP strength profiles were interpreted by identifying zones with varying RSP index values at different depths. These zones typically correspond to distinct snow layers, each with unique thicknesses and strength properties. This methodology is loosely based on a previous study that outlines how to determine the CBR strength of conventional materials with depth using DCP [24]. Their method of interpreting DCP was applied to RSP in the present study since RSP is similar in that it is analyzed by interpreting changes in resistance with depth to infer snow strength and layer boundaries. RSP is typically used to evaluate strength profiles across depth in dense snow, rather than to produce a single value. However, for the purposes of this study (i.e., comparing RSP results with single-value CBR measurements) it was necessary to adapt a method that integrates strength variations over depth. Although the referenced DCP methodology dates to 1994, it remains one of the few approaches describing how to condense depth-dependent penetration resistance into a single representative strength value [24]. This adaptation was necessary for comparison with single-value CBR results, as more recent literature does not provide an equivalent framework for RSP or DCP data.

As described previously, the three most closely related CBR values per testing event (i.e., each station and testing time point) are included in data analysis while the others are excluded (Section 2.2.1). This approach aligns with the procedures outlined in the CBR CRD-C 654 method, which requires re-testing in cases of high variability among replicates. For correlation purposes, any RSP replicate data corresponding to those CBR tests (i.e., RSP tests conducted at the same location and time) that were ultimately re-tested and demonstrated anomalies were excluded from the dataset as well. Additionally, the upper 0 to 25 mm of RSP data was excluded to eliminate potential effects of surface disturbance, consistent with standard practices in DCP data analysis procedure in accordance with ASTM D 6951 [25]. Field CBR measurements were conducted at the snow surface and represent approximately the upper 152 mm of the snow pavement. In contrast, the RSP provides a full-depth strength profile down to 400 mm. Obtaining CBR measurements deeper into the snow would have required digging test pits at each station for repeated measurements, which was not feasible because the study involved returning to the same locations over multiple time intervals; digging would have been a destructive sampling approach and would have compromised the integrity of the snow pavement. To ensure comparability between the two methods, only RSP data from 25 mm to 200 mm were included in the correlation analysis, closely aligning with the depth represented by the CBR measurements. From these filtered RSP data, a single mean RSP strength index was calculated for STA 1 and STA 2 at Tests 0–4, with deeper layers excluded to avoid introducing bias from layers not captured by the surface-focused CBR tests. After trimming, the dataset used for the correlation consisted of 10 paired observations, each representing a mean CBR measurement and a corresponding mean RSP reading at the aforementioned locations. Linear and non-linear (i.e., exponential and power law) regression models were evaluated using R for CBR over

time, RSP over time, and CBR versus RSP to investigate strength development over time and the relationship between CBR and RSP strength. After evaluating the overall fit (e.g., R^2 and residuals) of each linear and non-linear method, the linear fit was ultimately selected as the best fit and least complex method.

3. Results & Discussion

3.1. Snow Pavement Strength

3.1.1. CBR Strength Development

The CBR data demonstrate a general increase in snow pavement strength over time (Figure 4). Despite some scatter, particularly at intermediate time steps, the trend of increasing strength is evident. STA 1 showed a consistent strength gain, starting at a CBR of approximately 9 and reaching a maximum CBR of 15 by the end of the test period. STA 2 also exhibited strength gain but with greater variability. Initial CBR for STA 2 was roughly 8.5 and reached a maximum CBR of 21.5. These CBR values for both stations are in line with findings reported for field CBR direct measurement on snow (i.e., approximately 8 up to 32 for groomed snow) [6]. Average CBR trends reinforce a similar increasing pattern (Figure 5). At STA 1, the average CBR started at 8.9 and increased to 13.1 by the end of the testing period, reflecting a net gain of 4.2 percentage points (i.e., 47% increase). The standard deviation remained relatively low and consistent, ranging from 1.1% to 2.0%, with COV values between 11.0% and 15.9%. These moderate COV values indicate stable and reasonably uniform strength development at this location. STA 2 exhibited a more substantial strength increase, with CBR rising from 8.4 to 18.1, representing a gain of 9.7 percentage points (i.e., 115% increase). The standard deviation increased over time, reaching a peak of 3.8%, and the COV ranged from 8.6% to 21.2%. The higher variability observed at STA 2, particularly at the 28.8 h mark, suggests that while snow strength gains were greater, the horizontal uniformity of the snow layer was more variable than at STA 1. Overall, both stations showed clear increases in snow strength over time as measured by field CBR.

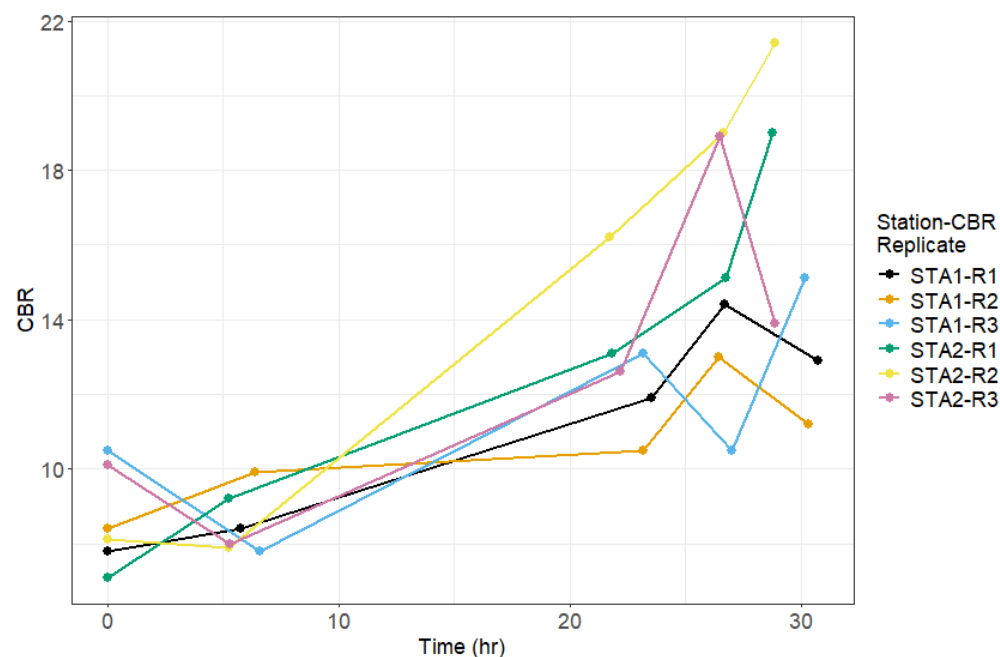


Figure 4. Time series of CBR measurements at STA 1 and STA 2, with three replicate tests at each station (R1–R3). Each line shows the CBR progression for an individual replicate, illustrating the spatial and small-scale variability in CBR response across stations.

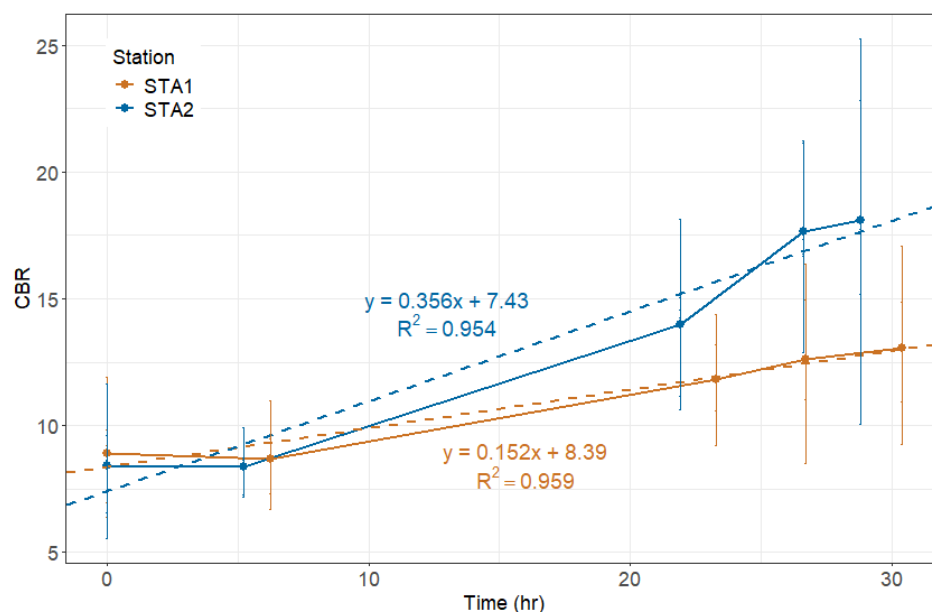


Figure 5. Mean CBR strength over time at STA 1 and STA 2. Error bars represent ± 1 standard deviation across the three replicate tests performed at each station and time point (i.e., Tests 0 through 4).

Linear regression models were applied to each data set to quantify the rate of strength gain (Figure 5). The fitted linear trends represent a simplified physical model of snow hardening, allowing the underlying rate of strength gain to be quantified despite small fluctuations in the raw data. In this context, the slope of each regression line reflects the average rate at which sintering and densification increase the load-bearing capacity of the snow pavement, while the intercept provides an estimate of the initial strength following construction. The slope represents the rate of change in average CBR per h. Both station trend lines indicate a positive linear relationship between elapsed time and field CBR. STA 2 exhibited a significantly steeper slope of 0.36 compared to STA 1 (i.e., 0.15), indicating a more rapid gain in snow strength over the 30 h observation period. The intercepts (i.e., 8.39 and 7.43 for STA 1 and STA2, respectively) suggest that, on average, snow pavements begin with an initial CBR near these values shortly after construction (in this case, 12 h). While STA 1 had a slightly higher initial average CBR value, STA 2 surpassed it within approximately 10 h and continued to increase at a faster rate. By the 30 h mark, STA 2 reached an average field CBR of approximately 18.5, while STA 1 reached an average CBR of 13.3. This corresponds to an overall strength increase of 11.1 units at STA 2 and 4.9 units at STA 1. The strong correlation coefficients (i.e., $R^2 > 0.95$) suggest the linear model provides a reliable representation of field strength trends for both stations. However, there is noticeable discrepancy in strength gain between the two stations. Some dispersion in the field CBR results is expected and reflects inherent variability in snow as a construction material. The difference between stations is likely due to several factors that could not be entirely controlled. Even under well-managed/controlled experimental setup, snow exhibits small-scale heterogeneity in density, moisture, grain bonding, and compaction effectiveness that can differ across a test section. These factors, along with minor operational inconsistencies, contribute to the observed scatter, particularly at STA 2. For example, while the stations were prepared in a similar fashion, STA 2 was tested approximately 3 h after STA 1. The temporal difference in testing likely allowed additional sintering and bonding at STA 2, resulting in a denser, more cohesive structure and explaining its greater strength gain. Despite this expected variability, the underlying strength-gain trends remain consistent and well-captured by the regression models. These findings emphasize the variability in snow

hardening behavior across the test area and highlight the importance of multi-point field verification when evaluating snow-supported surfaces. Importantly, the upward trend across the full-time domain reinforces earlier findings that snowpack strength increases measurably over time. The linear regressions support the viability of field CBR testing as a method for monitoring time-dependent strength gain in snow, offering direct, sensitive, and repeatable measurements. While operationally demanding, this approach proves especially valuable in controlled environments where accurate, time-stamped assessments of surface strength are critical for infrastructure performance or aircraft operations.

3.1.2. RSP Strength Development

The RSP data also demonstrate a general increase in snow pavement strength over time (Figure 6). Each data series represents a replicate RSP test which are colored to show the CBR replicates (e.g., Test 0, STA 1, Replicate 1) that they each correspond to. Vertical red lines indicate the minimum required RSP strength index to support an aircraft load of 227,000 kg [18]. The vertical dashed black lines indicate the average RSP index obtained by visually interpreting the trends in RSP index across depth (Section 2.2.2). Some RSP data showed clear separation in up to 3 layers (e.g., STA 2 during Test 2) while others were fairly uniform across depth (e.g., STA 2 during Test 0). Similarly to trends seen in CBR strength development over time, there were some slight decreases in RSP strength index during intermediary time points, but the general trend was upward. While not overly distinctive, many of the replicates (particularly STA 2) show higher RSP index values (i.e., stronger or more compacted snow) at shallower penetration depths as well as near the deepest penetration depth (i.e., near the surface of the underlying soil base layer), with slightly lower strength in the middle. This is expected as the ambient temperature of the FERF freezes the compacted snow from the surface downward, while the cold surface of the underlying soil material freezes from the base of the compacted snow upward.

At Test 0, conducted approximately 12 h after construction was completed, RSP strength values at both stations exhibited early signs of consistency and uniformity. This aligns with initial strength findings reported in a previous study that observed comparable RSP values in groomed snow [6]. At STA 1, RSP replicates ranged from a minimum of 8 to a maximum of 38, excluding one outlier of 73. Such deviations are expected due to natural heterogeneity within the snowpack or minor inconsistencies in test section preparation. For instance, hard clumps of snow that were not fully processed by the snowblower may have been incorporated into the compacted surface, leading to localized areas of increased strength due to differential freezing and compaction. At STA 2, RSP values ranged from 10 to 38, demonstrating slightly less variability than STA 1. Average RSP strength at STA 1 was 31 from the surface down to a depth of 200 mm, but decreased to 19 between 200 and 400 mm, indicating a notable decline in strength with depth. In contrast, STA 2 exhibited a more uniform strength profile throughout the full 400 mm depth, with an average RSP of approximately 30. These results suggest that despite some localized anomalies, the initial structural integrity of the snow pavement was relatively consistent between stations. In addition, these initial results contribute to the limited body of published data on snow pavement strength and represent one of the first efforts to characterize RSP over time rather than at a single location or time point. The strength values observed during Test 0 provide an important benchmark for understanding the early-stage behavior of snow pavement and suggest that it is capable of achieving an initial RSP strength around 30 within just 12 h of construction.

Following Test 0, a progressive increase in RSP strength was observed over the subsequent testing periods. During Test 1, strength increased by 18% at STA 1 and 38% at STA 2. In Test 2, RSP strength continued to rise, with additional gains of 15% at STA 1 and 9% at

STA 2. By Test 3, however, a divergence in trends emerged: the average RSP strength at STA 1 decreased by 11.8% relative to Test 2, returning to a value of 30, while STA 2 exhibited a further strength increase of 6.7%. At the conclusion of the study, Test 4 results indicated a cumulative strength increase of 28% at STA 1 and 80% at STA 2 over the 30 h testing period (from Test 0 to Test 4), highlighting ongoing consolidation and strength development under the given conditions. The variability in RSP values similarly reflects natural heterogeneity within the snowpack, the presence of locally harder inclusions, depth-dependent freezing rates, and differences in sintering time between stations. These mechanisms collectively explain the replicate-to-replicate dispersion in the RSP index while still supporting the overall trend of increasing strength with time. Strength gain of the compacted snow was expected since the compaction activities catalyze the sintering process. Sintering occurs when two snow grains come into contact and water vapor or liquid water migrates across their surfaces, forming small ‘necks’ that fuse the grains together [26]. These bonds strengthen the snow structure over time. Since the temperature in the FERF was kept constant throughout the experiment, there was no significant warming to increase moisture content. This likely limited the achievable level of strength, as a slight temperature rise can enhance sintering by increasing the availability of moisture. In field applications, where natural temperature fluctuations can promote sintering, strength gains may be greater but also introduce the potential for melt and therefore low bearing strength of the snow pavement. Alternatively, water can be manually added to encourage bonding and achieve similar improvements in strength under controlled conditions [16]. Moisture was not manually added during this experiment since the purpose was not to achieve significant strength gain, but to instead evaluate the ability to capture strength development with both CBR and RSP testing.

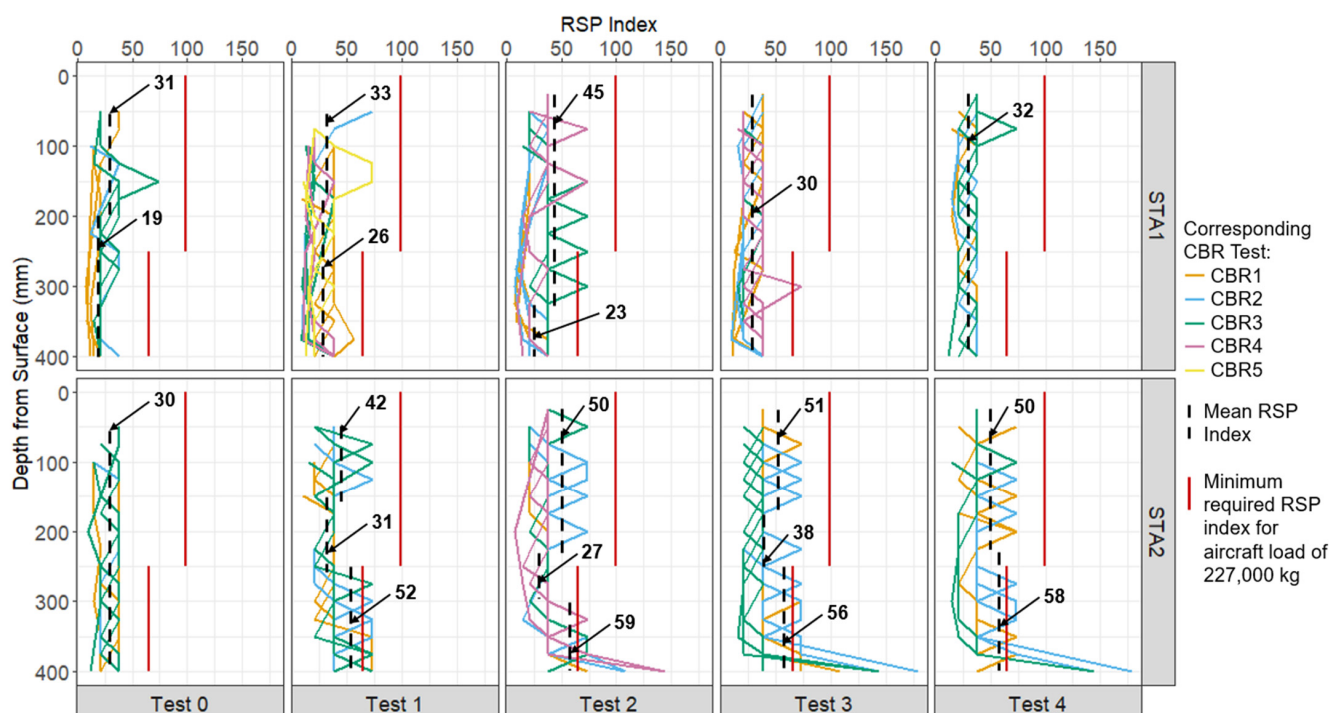


Figure 6. RSP index across penetration depth (mm) for STA 1 and STA 2 (vertical facet) during Test 0 through 4 (horizontal facet). Each data series represents a replicate RSP test which are colored to show the CBR test replicates (e.g., Test 0, STA 1, Replicate 1) that they each correspond to (i.e., there were 3 RSP replicate at every 1 CBR replicate location). Vertical red lines indicate the minimum required RSP strength index to support an aircraft load of 227,000 kg [18]. The vertical dashed black lines indicate mean RSP index determined using a method derived from [24].

Obtaining a single average RSP strength index for each station during each test (i.e., Test 0–4) and plotting it over time provides a more direct assessment of strength development and the rate of strength gain over the course of the study (Figure 7). Although there was a decrease at Test 3/STA 1, overall average RSP strength across depth at STA 1 and STA 2 increased from 25 to 32 (i.e., +7) and 30 to 54 (i.e., +24), respectively, demonstrating modest but evident strength gain within the entire testing duration. Linear regression models for each station quantify the rate of strength gain, with the slope representing the rate of change in average RSP per h. Although the dataset contains only four non-initial time points, the fitted linear trends serve as a simple, first-order representation of snow hardening, allowing the average rate of sintering-driven strength gain to be quantified. In this context, the slope provides a physically interpretable measure of how rapidly bonding and densification increase the RSP index, while the intercept approximates the initial mechanical state of the snow surface at each station. Similar to the trends observed in the CBR strength results, STA 2 also exhibited a significantly steeper slope (0.63) compared to STA 1 (0.20), indicating more rapid strength gain over time. Both regression models also have moderate to strong correlation coefficients ($R^2 = 0.62$ and 0.81 for STA 1 and STA 2, respectively), indicating a reliable representation of RSP strength gain over time. Like the CBR results, RSP measurements of the snow pavement revealed that the strength at STA 2 was consistently greater than at STA 1. STA 1 was tested first following construction completion, whereas STA 2 was evaluated approximately 3 h later. This temporal difference, especially early after compaction activities where the faster strength gain development is expected, may have allowed for additional sintering and bonding between snow grains at STA 2, resulting in a denser, more cohesive snow structure. By adjusting the STA 1 data to exclude the first time point and instead “begin” 3 h later, the y-intercepts move closer together between the two stations showing greater consistency between initial RSP index of the snow pavement (i.e., STA 1 = 29.4 and STA 2 = 33.5). The observed increase in strength at STA 2 is therefore likely attributable, at least in part, to this extended sintering period, highlighting the importance of time-dependent processes in the mechanical development of compacted snow surfaces.

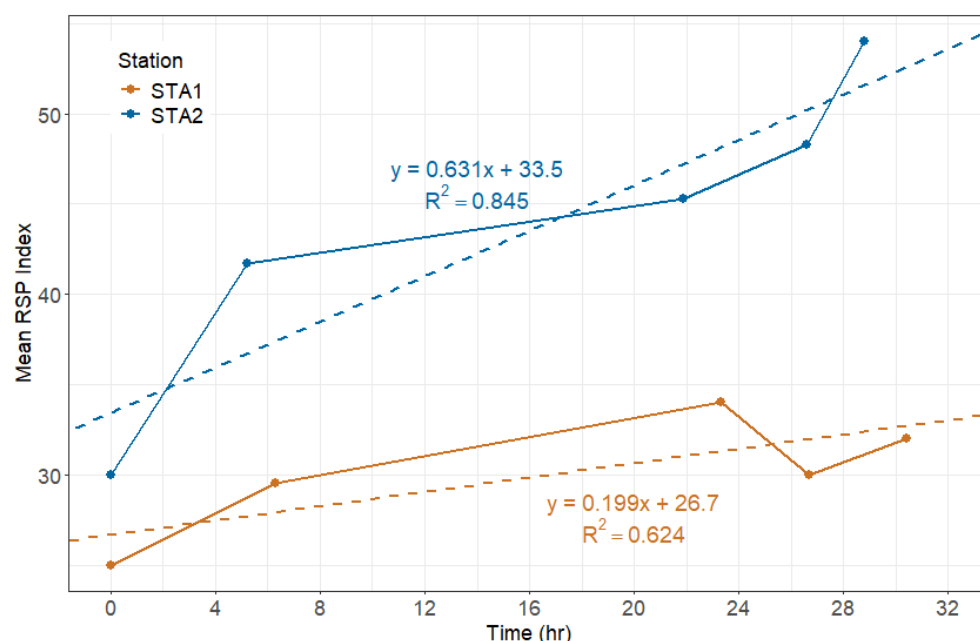


Figure 7. Mean RSP strength index over time at STA 1 and STA 2. Error bars are not shown due to the method in which mean RSP index was visually determined, adopted from a similar method used in a previous DCP-related study [24].

3.2. RSP and CBR Correlation

Since trends in snow pavement strength development over time aligned well between CBR and RSP values, correlation between the two was promising. The linear regression analysis produced a coefficient of determination of $R^2 = 0.44$, indicating a moderate positive correlation between CBR and RSP values (Figure 8). While the sample size is small (i.e., $n = 10$), this analysis serves as a starting point for evaluating the potential of using RSP as a proxy or supporting indicator for CBR strength. This relationship between CBR and RSP strength index exhibits some scatter, which is expected given the limited number of paired measurements and the inherent differences between the two testing methods. Although RSP and CBR were collected in close proximity and within minutes of one another, small spatial offsets and unavoidable temporal lags likely contributed to measurement variability. Differences in loading mechanisms and sensitivity to local heterogeneity can further amplify variability. These combined factors help explain the moderate correlation ($R^2 = 0.44$) and the spread of the data in Figure 8. Despite this variability, the observed trend still reflects a consistent increase in CBR with increasing RSP index across both test stations. The linear regression performed here is intended as an empirical first step to quantify the observed relationship between RSP and CBR measurements. It does not represent a mechanistic or physically derived conversion, and the strength of this correlation is not sufficient to propose a generalizable conversion model at this stage. Instead, this is a foundational analysis demonstrating that the two methods capture overlapping aspects of snow strength development over time and space, and that paired measurements show enough coherence to justify further investigation. In other words, these results begin to show the potential for using the simple, streamlined RSP test method for field applications in extreme cold conditions then converting the data into well-understood field CBR strength values. Further investigation with additional paired measurements and exploration of the physical processes governing snow strength development (e.g., sintering, densification, and bonding) will be necessary to develop a mechanistic or generalizable conversion framework. Building upon the dataset will help develop a formal conversion framework, where the translation between the two will be a crucial part of evaluating snow pavement strength for infrastructure in cold environments (e.g., roads, airfields, and construction pads/foundations).

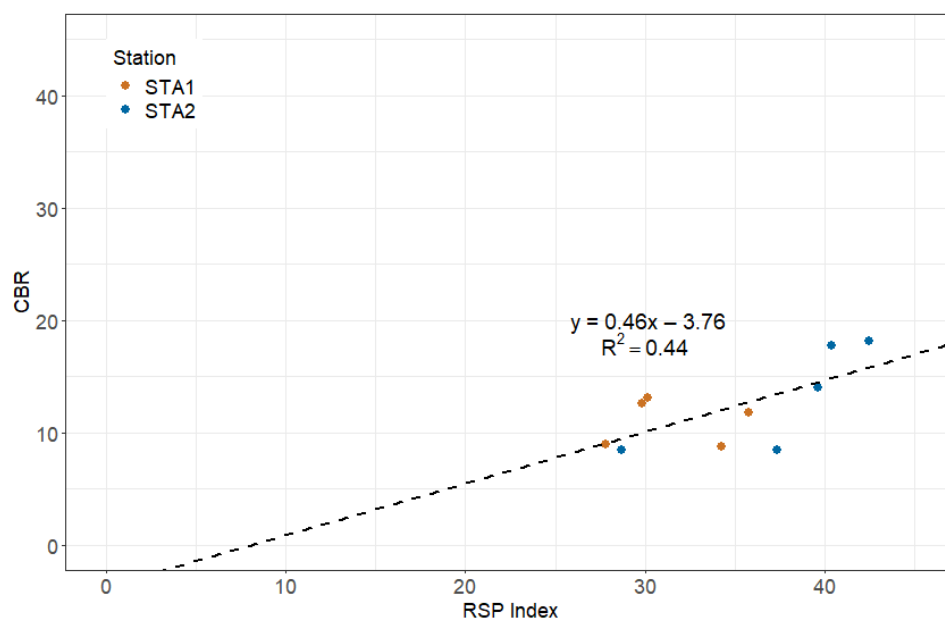


Figure 8. CBR strength plotted against RSP strength for all tests conducted at STA 1 and STA 2. A linear best-fit line and correlation coefficient (R^2) are included to quantify the relationship between the two snow pavement strength measures.

To build upon the findings of this study, future work should prioritize expanding the dataset through additional side-by-side CBR and RSP testing to strengthen the correlation between the two methods. This will enable refinement of the RSP–CBR correlation model, ultimately leading to a more efficient, scalable framework for evaluating snow-supported surfaces in operational environments. Specifically, conducting CBR testing with depth, rather than only at the surface, would enable more direct comparisons to the RSP’s full-depth strength profiles. Future testing should also encompass a broader temperature spectrum to evaluate thermal effects on strength gain through fluctuation moisture content. Testing should be replicated across multiple locations and time intervals to improve statistical robustness and account for spatial variability in snow properties. Evaluating test performance under simulated aircraft loading throughout the process would also provide valuable validation of the predictive accuracy of the developing correlation model (i.e., using RSP to estimate CBR for decision-making). Complementary use of additional strength characterization tools, such as the DCP is recommended to enhance cross-validation efforts with previously developed models [12,18–20].

3.3. Limitations

Several limitations should be considered when interpreting the results of this study, most of which reflect practical constraints inherent to conducting controlled snow pavement experiments. First, the sample size for paired RSP–CBR measurements was limited ($n = 10$) due to the labor-intensive nature of full-scale snow pavement testing and the need to perform repeated measurements at multiple time points. Second, CBR measurements were restricted to the upper ~152 mm of the snow pavement because obtaining deeper measurements would require destructive test pits, which were not feasible given the repeated testing at the same locations over time. Third, although RSP measurements were collected immediately prior to each CBR test to approximate side-by-side measurements, a small spatiotemporal lag was unavoidable due to the need to relocate and set up the CBR apparatus at the same spot. Alternatively, we could have collected CBR and RSP data at the exact same time, but to do so would require a trade off in that they not be collected in the exact same spot instead. Fourth, the study was conducted under a constant temperature in the FERF to remove temperature as an additional variable while establishing baseline CBR values for snow and comparing them to RSP, though this limits direct applicability to environments with naturally fluctuating temperatures. Fifth, the relatively short testing period (~30 h) reflects operational constraints, and the typical snow “curing” period used in snow engineering, though longer-term trends or seasonal effects were not captured. Sixth, two different CBR kits (CRREL and GSL) were employed; while both adhered to standard procedures and produced comparable results, direct side-by-side validation was not possible due to the end of the FERF refrigeration season. Finally, the linear regression used to correlate RSP and CBR values represents an initial, foundational analysis intended to explore the relationship between the two methods; it is not a predictive model, and more extensive paired testing would be needed to develop a formal conversion framework. Despite these limitations, the study provides important insights into snow pavement strength development and demonstrates a practical approach for directly comparing RSP and CBR in a controlled, operationally relevant setting, laying the groundwork for future research and field applications.

4. Conclusions

This investigation aimed to determine whether field CBR testing could reliably capture the time-dependent strength gain of compacted snow pavements. In parallel, the study

evaluated the potential for correlating results from the RSP, a device traditionally used to assess snow strength, with field CBR measurements.

Field measurements demonstrated that compacted snow pavements gain measurable strength over time following construction. Both CBR and RSP testing successfully captured these time-dependent increases, with higher values consistently observed at STA 2 due to extended sintering and improved compaction. The agreement between methods confirms that each is sensitive to localized variations in snow strength.

Paired RSP and CBR measurements showed a moderate linear relationship ($R^2 = 0.44$), suggesting that the RSP has potential to serve as a proxy for CBR-derived strength indices in snow. However, this level of correlation also indicates that the two methods currently capture overlapping but not identical aspects of snow strength, underscoring the continued value of performing both tests during early-stage evaluation. While the sample size was limited ($n = 10$), the observed correlation supports continued investigation into quantifying this relationship for broader application.

These findings begin to establish the foundation for relating snow-specific strength measurements to traditional pavement evaluation methods. Expanding the dataset and refining the RSP–CBR correlation will be essential to developing robust guidance for snow pavement design and assessment, particularly for supporting aircraft operations on compacted snow runways in cold environments. To achieve this, future work should focus on conducting additional paired CBR and RSP testing under a wider range of snow types, temperatures, and compaction conditions to strengthen and refine the observed correlation. Conducting CBR testing with depth, rather than only at the surface, would also enable more direct comparison with the RSP's full-depth strength profiles. Broader testing campaigns across multiple sites and under varying operational conditions will help improve statistical robustness and assess real-world applicability. Finally, extending the evaluation to other field devices, such as the DCP or Clegg hammer, could provide valuable cross-validation and further advance the development of reliable, field-deployable methods for assessing snow pavement strength.

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Abbreviations

The following abbreviations are used in this manuscript:

ASTM	American Society for Testing and Materials
CBR	California Bearing Ratio
CRREL	Cold Regions Research and Engineering Laboratory
C/L	Centerline
DCP	Dynamic Cone Penetrometer
FERF	Frost Effects Research Facility
GSL	Geotechnical and Structures Laboratory
RSP	Russian Snow Penetrometer
STA	Station
USACE	United States Army Corps of Engineers

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