USE OF WEATHERED ROCK FOR ENGINEERED FILL IN PERMAFROST REGIONS OF ALASKA

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Abstract

Civil construction projects in permafrost areas typically require large quantities of granular materials for construction of foundation pads, roadways, and other engineered fills. The Red Dog Project in Northwestern Alaska lies entirely within permafrost terrain that has no suitable natural sand and gravel deposits. Development of the mine required construction of a 52 mile haul road across the tundra, as well as tailings dams, and pads for mill site foundations. All of the construction materials were processed from quarries excavated into highly weathered, frost fractured permafrost rock. This paper describes procedures that were used for evaluation of construction material sources and criteria adopted to improve performance of the engineered fills.

Geotechnical investigations, laboratory studies and construction surveillance all showed that lithology and *in-situ* ice content are the key parameters that control acceptability of a construction material source. Field and laboratory investigation programs must be planned and executed with a standard of care beyond that of conventional borrow source evaluation to avoid misleading information and costly surprises during construction.

Résumé

Les projets de construction dans les régions pergélisolées nécessitent habituellement d'importantes quantités de matériaux granulaires pour l'établissement de remblais, de chaussées et à des fins de remplissage. Le développement minier de Red Dog, dans la partie nord-ouest de l'Alaska se situe entièrement sur un terrain pergélisolé dénué de dépôts naturels de sable et de gravier de qualité acceptable. Le développement de la mine nécessitait la construction d'un chemin de hâlage de 52 miles à travers la toundra ainsi que des digues de terrils et de remblais comme fondations pour le moulin. Tous les matériaux de construction furent préparés à partir de l'exploitation de carrières dans du roc très météorisé et gélifracté. Cet article décrit les procédures utilisées pour l'évaluation des bancs d'emprunts et les critères adoptés pour améliorer le comportement des matériaux de remplissages préparés.

Les investigations géotechniques, les tests de laboratoires et la surveillance de chantier ont montré que la lithologie et la teneur en glace *in situ* sont les principaux paramètres qui régissent l'acceptabilité d'une source d'emprunt de matériaux de construction. Dans ce genre de milieu, il est nécessaire d'établir des protocoles adaptés d'investigation sur le terrain et en laboratoire et de les suivre plus soigneusement qu'on ne le fait dans le cas des emprunts conventionnels, autrement l'information obtenue est biaisée et de coûteuses surprises peuvent survenir durant la construction.

Introduction

Road construction over ice rich permafrost terrain requires substantial quantities of granular materials to maintain a grade with continuous fill over thaw sensitive terrain. A 52 mile long haul road was required to connect the Red Dog Mine site in the DeLong Mountains in Northwestern Alaska to a port on the coast of the Chukchi Sea. The lead and zinc concentrate produced at the mine site will be trucked to the seaport for storage during winter months and then loaded and transported by vessel to southern smelters during summer open water periods.

Early in the planning process it was recognized that there were limited sources of natural sand and gravel within the broad mountain valley that forms a natural corridor for the road. Therefore all of the construction materials were processed from quarries excavated into highly weathered outcrops of permafrost sedimentary rocks that form the upper valley slopes.

The DeLong Mountains haul road required the development of thirteen material sources along its length as shown in Figure 1. The resulting construction materials were derived from rocks of varying lithology, primarily siltstones and mudstones, shales, cherts, and sandstones. This paper provides a summary of methods used to evaluate potential quarry sources and pertinent construction observations.

Construction of haul roads and support facilities with permafrost rock created particular challenges for quarrying, processing and placement operations. Acceptable

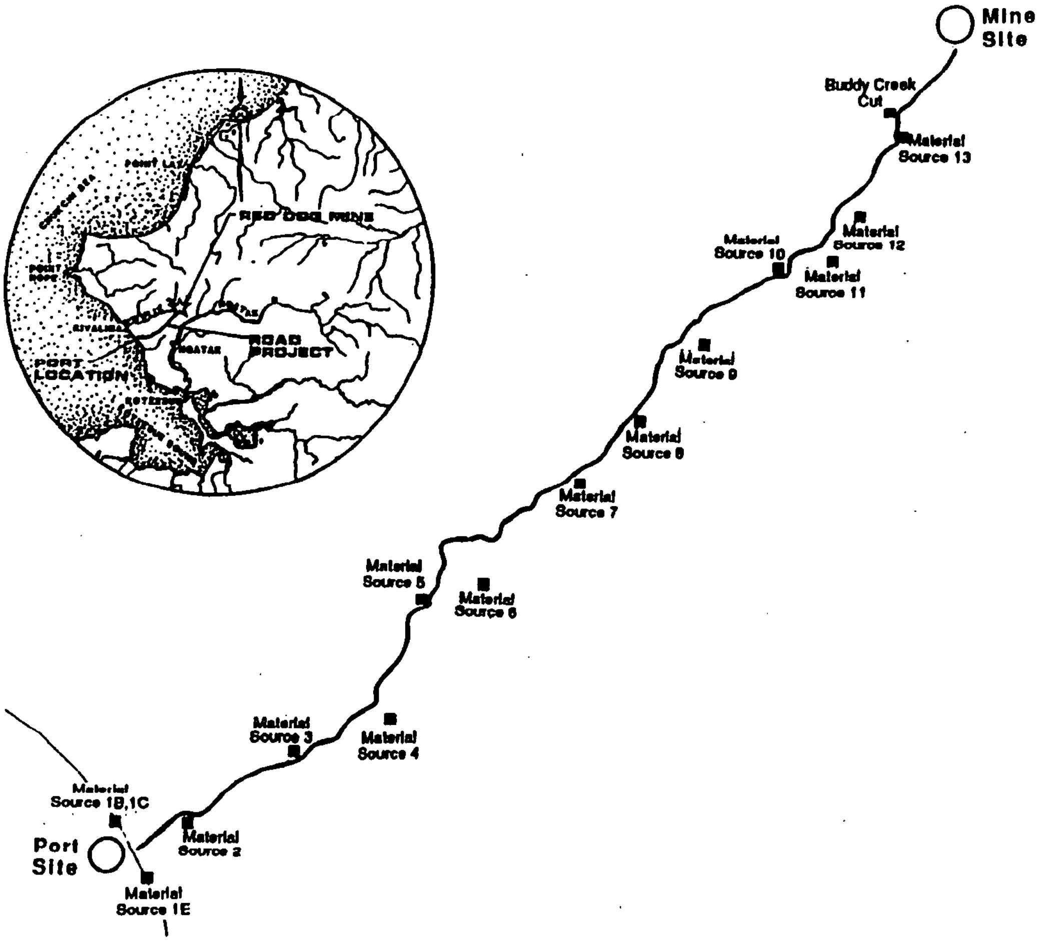

Figure 1. Material source location map.

performance of these materials under severe loads could not be predicted with confidence. The paper addresses the following topics pertinent to the successful selection and use of these materials: 1) Regional geology and the selection of the material sources; 2) Laboratory performance testing of processed rock; 3) Construction use and performance of the quarried rock and processed rock, and 4) An engineering evaluation of the long term performance of engineered fills constructed from "soft" permafrost rock in an arctic environment.

Material Source evaluation

The Red Dog Mine site is located in a western extension of the DeLong Mountains in the northwestern section of the Brooks Range physiographic region. This region is north of the Arctic Circle in a zone of continuous permafrost. The topography near the mine site is comprised of sharp topographic rises and pronounced east-west trending ridges. The coastal plain extending along the coast of the Chukchi Sea is of an undulating topography consisting of low rounded hills, relict coastlines, lagoons, broad deltas, spits, and bars.

The region is characterized by varying thicknesses of residual and colluvial soils overlying shallow sedimentary and metamorphic rocks. The presence of ground water during the winter was evidenced throughout the region by aufeis formation along topographic breaks and drainages. Vegetation consists of typical arctic sedges and tussocks, with limited occurrences of willows.

The DeLong Mountains consist primarily of slightly metamorphosed, folded and faulted sedimentary rocks. The folded and faulted topography results in a complex discontinuous stratigraphic section. The bedrock has been interpreted to be Mississippian or older (Devonian) in age. Rocks typical to the region include quartzite, quartzose sandstones, shale, and clay shale, chert, sandstones with subordinate chert, siltstone and indurated mudstones, dolomite, and forms of limestones (Tailleur, 1975).

The upland regions west to the southwest of the DeLong Mountains have experienced varying degree of glaciation during the Pleistocene, resulting in glacial infill between bedrock controlled topographic features, and scattered landforms. Glacial infill within the exposed bedrock structure has typically produced long footslopes. Glacial landforms observed to within a few miles of the coast are comprised of kames and moraines.

Surficial soil conditions present throughout the DeLong Mountains have primarily developed through in-place weathering of bedrock exposed at the surface. As a result, each bedrock formation possesses its own unique topography, drainage patterns, soil types, and ground ice conditions. Weathering of the bedrock and residual soils by frost action, erosion, and mass wasting have produced varying soil profiles. Residual soil profiles varied in thickness, were typically fine grained, and exhibited characteristics that are closely associated with the lithology of bedrock formations common to the region. Colluvial soil profiles are prevalent on lower slopes of major topographic rises. These soils commonly contain higher ground ice contents, as well as massive ice inclusions.

Similar permafrost bedrock conditions were observed on Melville Island in the Canadian High Arctic Islands. The region is characterized by sandstone and siltstone bedrock and scattered glacial landforms. Stangl et al (1982) reported that geotechnical properties of the surficial soils at Melville Island were closely related to the structure, age, and lithology of the bedrock. From their observations the degree of weathering and degradation of the bedrock was dependent on the lithology and the degree of cementation of the "parent" rock.

The integration of the physical setting, geologic conditions, and geotechnical characteristics of the rock materials and residual soils after processing was carefully considered before selecting potential material sources. The residual soils in the region are typically composed of silts and clays, silty sands, coarse sands, and silty sands and gravels. This indicates that, through weathering and degradation, the optimum bedrock sources for construction materials would be the sandstones, cherts and the well indurated shales. Efforts were directed at avoiding the ice rich materials and the "soft" or weaker bedrock, such as the Kivalina clay shales, siltstones, and mudstones. Material source evaluations were frequently complicated by thinly bedded, steeply dipping strata. The conventional practice of correlating material properties between exploratory boreholes was often misleading.

As quarry operations progressed during haul road construction, early November 1987 to August 1988, observed differences in material, ice contents, and availability became of concern. Material sites that were logged initially as acceptable sources for road surfacing and other structural backfill applications were found to be of limited quantity and quality. The discrepancies were observed primarily in the material source where the initial borehole information relied on conventional augering with limited drive sampling, and borehole logging of the bedrock stratigraphy from chip samples. The discrepancies, including material type, quality, ice content, and stratigraphic breaks could be attributed to site investigation techniques or limitations.

The sites were re-evaluated by the authors using *continuous coring techniques*. Conventional air coring techniques were modified to include changes to diamond bits, inclusion of heat exchangers for chilling air to the bit, additives such as foam to facilitate removal of cuttings, and controlling the volume of air with the drill rate. Successful results of the air coring of frozen ice rich rock can be seen in the photograph presented in Figure 2. The coring operations produced frozen rock core recovery averaging 80 percent of the total core run during the site investigation. Successful results were obtained in bedrock stratigraphy with RQD (rock quality designation) ranging from 5 to 40 percent. The recovered core was then tested and natural moisture content, ice content, and representative durability values determined. The natural *in-situ* properties could then be used to estimate full performance properties and specify the most appropriate use during construction.

Laboratory Testing of Processed Rock

Laboratory testing programs for evaluating borrow materials for use as engineered fills are generally directed at determining grain size distribution, natural moisture content, moisture-density relationships, and durability. Preliminary laboratory data from the early site investigations were found to be inadequate for characterization of material suitability. Early in the construction, excavated materials were found to be unacceptable or marginal for structural fill or road surfacing due to excessive ice contents or poor durability associated with changes in lithology. As construction

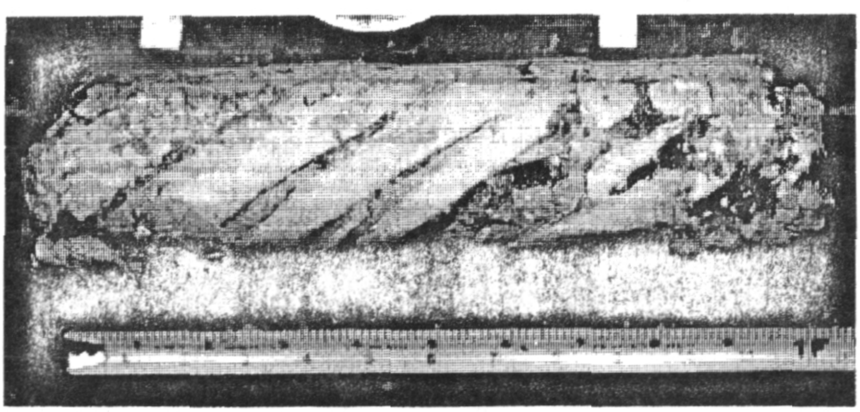

Figure 2. Ice rich rock obtained by air coring (HW core).

activities progressed, additional testing was required to determine and verify the use of the available rock in the developed material sources. Laboratory testing programs were directed at evaluating durability and placement performance of the processed materials during construction.

Durability testing of the rock sources consisted of L. A. Abrasion (ASTM C-131), Sodium Sulfate Soundness (ASTM C-88), and the State of Alaska Test Method T-13 (ATM T-13). Durability testing standards were established by the Red Dog Project designers for use of rock materials for road surfacing, offshore fill, and concrete aggregate. Typical test results from a slightly metamorphosed sandstone and chert ("hard") rock sources compared to a siltstone ("soft") rock source are presented in Table 1. Durability test data were found to vary substantially between sources and were dependent on weathering and degree of cementation of the "parent" rock.

The State of Alaska Test Method T-13 is intended to determine the susceptibility of an aggregate to degradation during agitation in water. Representative samples were selected from each core section, crushed and washed over the No. 10 sieve, and allowed to dry. Each sample was then separated into two samples of 500 grams, one sample containing the 1/2-inch to 1/4-inch fraction and the second sample containing the 1/4-inch to No. 10 fraction. Each sample was put into a water-filled plastic container and vibrated in a sieve shaker at 300 horizontal oscillations per minute for twenty minutes. The cannister was then washed over a No. 10 and No. 200 sieve with 500 ml of water into a graduated cylinder. Then 7 ml of stock sand solution was poured into a sand equivalent cylinder. The graduated cylinder was tipped upside down ten times to bring the sediment into suspension and poured into the sand equivalent cylinder up to the 15 inch mark. The contents were then mixed in the sand equivalent cylinder by allowing the bubble to traverse from one end and back again, 20 times as rapidly as possible. The cylinder was allowed to sit undisturbed for 20 minutes before recording the sediment height. The recorded height provided the data for calculating the degradation factor (D).

Abrasion resistance testing provides an indication of material durability during handling, stockpiling, and placement. A sample of crushed rock was prepared to Grading A specifications (between 1-1/2 to 3/8 inches in diameter). The sample was placed in the Los Angeles machine along with twelve steel spheres, and rotated for 500 revolutions at 30 to 33 revolution (5 per minute). The sample was sieved again on a No. 12 sieve and the material retained on the No. 12 sieve (final weight) weighed. The loss (percentage of wear) is the difference between the original and final weights of the tested material expressed as a percentage of the original weight.

The ability to resist particle breakdown when subjected to repeated immersion in a sodium sulfate solution is a measure of the absorption characteristics and pore structure of the aggregate. It is an index to the "soundness" of the material. Fine and coarse aggregates are immersed in a sodium sulfate solution, followed by draining and oven drying. The liquid penetrates the interstices of individual particles, which upon drying creates internal stresses causing splitting, crumbling, and flaking of the surface. Typically, five immersion cycles are performed. After washing and drying the sample is visually examined and sieved again to determine changes in particle size. Results are reported as "percentage loss", which is measured as the percentage by weight which passes a sieve on which the particles were originally retained.

Results of comparative testing performed between a laboratory sample prepared solely for testing in accordance with the State of Alaska Test Method T-13 to that of a sample prepared from a previously tested abrasion sample shows a significant increase in the durability results are obtained (Table 1). This increase could be attributed to the elimination of weak fractures from crushing or the overbreakage of weak lithofacies during the initial testing, thus eliminating the source of loss from the second test. The mechanical loss and change in grain size associated with crushing, material handling, and placement should be considered when evaluating and specifying a grain size for processed materials. In comparison to natural deposits of sand and gravels, which are typically subrounded to subangular, the differences in degradation values could be attributed to the natural processes that developed the deposit. The loss during placement should be less than that for the processed materials.

Natural moisture contents of the rock were observed to vary from less than 1 percent to as much as 20 percent. Natural moisture contents were found to be directly dependent on the percentage of visible ice present in the rock sample. Moisture contents (ice contents) were higher at the transition between residual soils and the bedrock, or where excessive fracturing associated with freeze thaw degradation was encountered. Fine grained, thin and poorly laminated rocks, such as siltstones and clay shales (Kivalina Shale), typically had higher moisture (ice) contents than the fine to medium grained, blocky sources of sandstone, chert and

Table1. Summary of durability testing

Source	Material testing	L.A. Abrasion ASTM C-131	ATM T-13 (State of AK)	ATMT-13 L.A. sample	Soundness ASTM C-88
MS-12	sandstone	18%	75%	93%	0.8%
MS-6	siltstone	28%	1%	23%	14%
MS-9	chert	11%	89%	96%	
specification		45% max	45% min	45% min	5% max

shale (Sisipuk Shale). Massive ice and wedge ice was found throughout the Kivalina clay shale. Where this material was found in conjunction with acceptable materials, it was stripped and wasted. Moisture contents in most bedrock sources were observed to be typically less than 5 percent, and decreased with depth depending on the extent of weathering.

Moisture-density relationship determinations by Modified Proctor (ASTM 1557) were found to be acceptable for gradations which conformed to methods in the test procedures. When oversized rock, greater than 3/4 inch in diameter, constituted greater than 30 percent of the source, the materials were not in conformance to specified test methods, and maximum-minimum density relationships were then required. Test results of rock sources crushed to a 2 inch minus gradation were similar to that of a sandy gravel. Dry densities were observed to range from 140 to 146 pounds per cubic foot (pcf), with optimum moisture contents of 4 to 7 percent. Variations in optimum moisture content and dry density were dependent on the lithology of the rock sources, as shown in Table 2.

Table 2. Moisture density relationships

Materail Type	*Maximum Density (pcf)	Optimum moisture Content (%)
Chert	140	4.0
Sandstone	144	6.5
Siltstone	142	7.0

*From ASTM 1557 modified proctor compaction tests

Maximum dry density values reported in Table 2 are from samples crushed to a 2 inch minus road surface specification for the Red Dog Project (Fig. 3). The density values include the State of Alaska Test Method T-11 rock correction factor. Higher optimum moisture contents observed during laboratory testing were associated with breakdown of the materials during placement in the Proctor mold.

Similarly, testing to determine frozen moisture-density and thaw strain relationships were dependent on particle breakdown during preparation of the samples. Frozen moisture density testing was performed in the laboratory by freezing a crushed rock sample to a predetermined moisture content. The samples were then broken into pieces and compacted in a modified Proctor Mold. The samples were then allowed to thaw with a normal (1 ksf) surcharge load. The change in height with was recorded. Figure 4 presents a comparison of chert, sandstone, and siltstone during frozen moisture-density testing. In comparing the moisture-density relationships, the blocky and angular chert samples experienced the least amount of breakdown during testing and developed a higher frozen compacted density. In comparing similar sedimentary rock sources, such as the sand and siltstones, the moisture-density relationships were observed to be dependent on breakdown of the clasts when placed in a compaction mold. The sandstone experienced some breakdown of the rock clasts, becoming subangular with some bridging in the Proctor mold. As frozen moisture content increased in the samples, density decreased as mineral clasts were replaced with ice particles. The siltstone, in comparison to the sandstone, produced greater density values primarily due to extensive breakdown and packing of

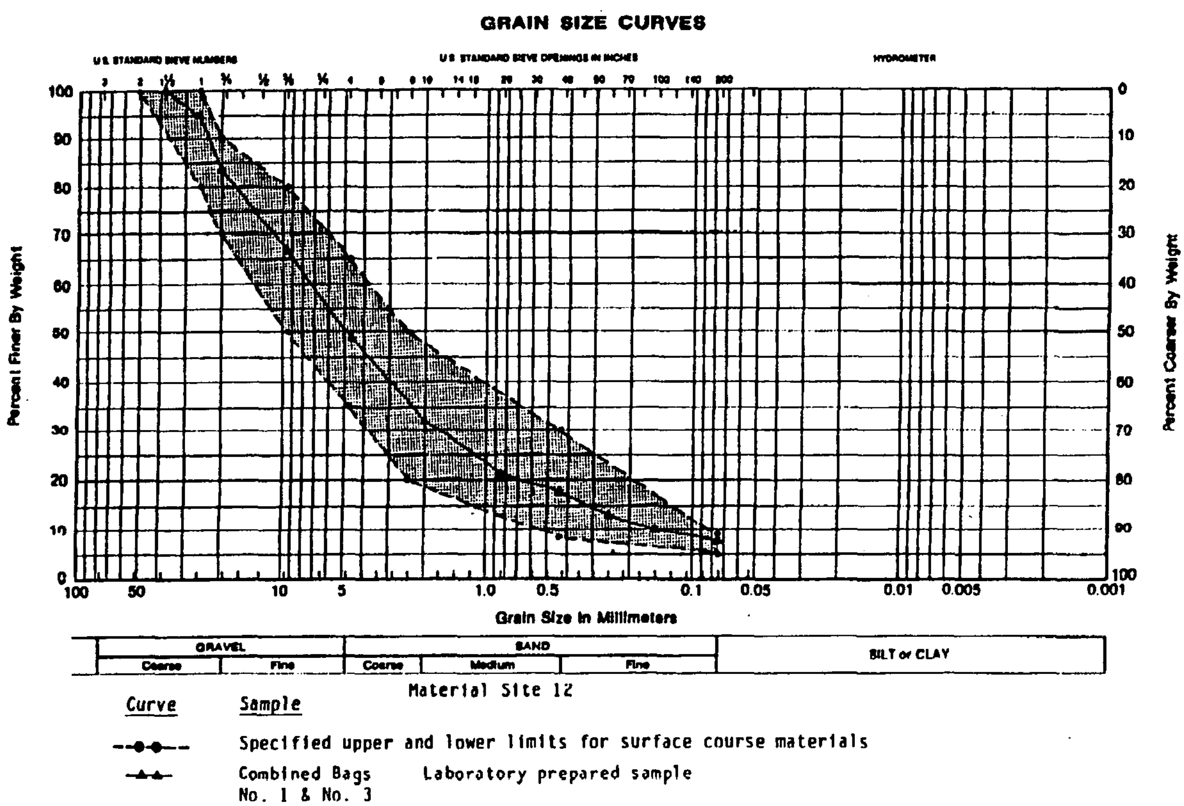

Figure 3. Grain size distribution for laboratory testing.

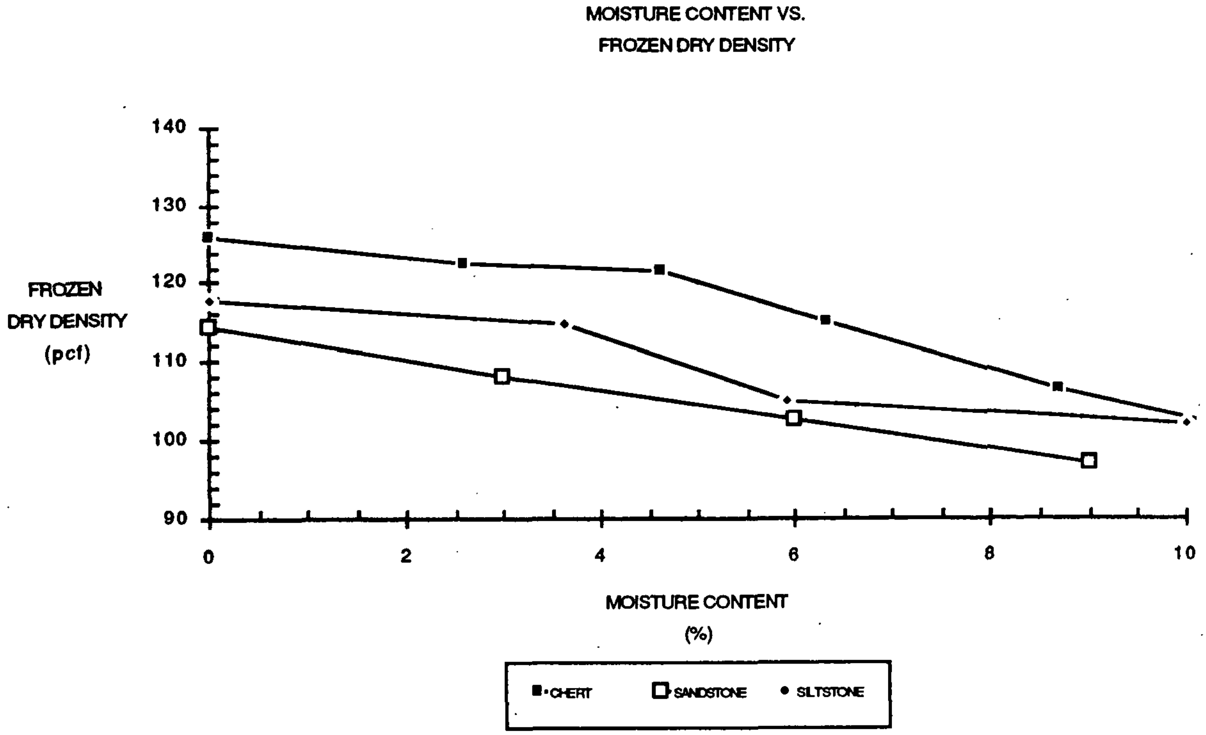

Figure 4. Frozen moisture - density relationships.

the clasts during placement in the compaction mold. In the rock materials with lower durability, the particle sizes broke down, producing a higher density.

Thaw strain testing was performed on the samples prepared in the laboratory for frozen moisture-density relationships to observe their winter placement characteristics. The resulting thaw strains of the processed rock materials were observed to be lower than those values previously reported by Lusher and Afifi (1973). The values were also lower than those reported by Scher (1982) for natural sand and gravels (Fig. 5). The thaw strain values for the processed rock appear to be dependent on the extent of breakdown during placement and the degree of bridging across the ice and rock clasts. Figure 6 presents results of thaw strain testing performed on chert, sandstone, and siltstone samples. The siltstone produced the highest thaw strain values and, comparatively, the chert produced the lowest test results. The placement density of the processed rock is dependent on the strength or durability of the clasts, or the resulting clast size in place, the percent of frozen moisture (ice), and the method of densification to minimize bridging between rock and ice clasts. Thaw strain became significant at dry densities less than 112 pcf (Fig. 5). This was an important consideration in the selection of materials for engineered fills to support shallow footings for the mill site complex.

Construction performance observations

Civil construction techniques utilized during the Red Dog Project for the haul road, dams, and initial mine site facilities were similar. Excavation and hauling were centered around a drill and blast program. Blasted materials were then "mucked" from the shot by front end loaders (typically Caterpillar 988 or 992 series equipment) and hauled by off highway trucks (typically Terex R-35 and Caterpillar 777). Selected sources were then processed through rock crushers, "Grizzly" screens, and conventional screening plants as applicable to develop specified gradations. Fill operations were performed by end dumping from the trucks and spreading to specified lift thickness by bulldozer (Caterpillar D-9 or equivalent). The fill was then compacted using self-propelled vibratory static drum compactors.

The drilling and blasting operations experienced some difficulties with in-situ ice contents and discontinuities in the rock. Drilling was performed using conventional air percussion construction drills. Drilling in high ice content materials was slow and experienced difficulties clearing cuttings from the borings. The fractured and weathered structure of the rock frequently caused hole collapse which required overdrilling and redrills. In some instances, free water was encountered and the holes flooded and froze, prohibiting loading operations. Blasting efficiencies were notably less in the "soft" siltstones, shales, mudstones, and rock containing high ice.

The energy from the blast was "dampened" under these conditions, producing less breakage and considerable oversized materials, compared to rock with a dry intact structure which can produce adequate breakage, limiting the amount of oversized materials and secondary handing to meet some of the coarser rock specifications.

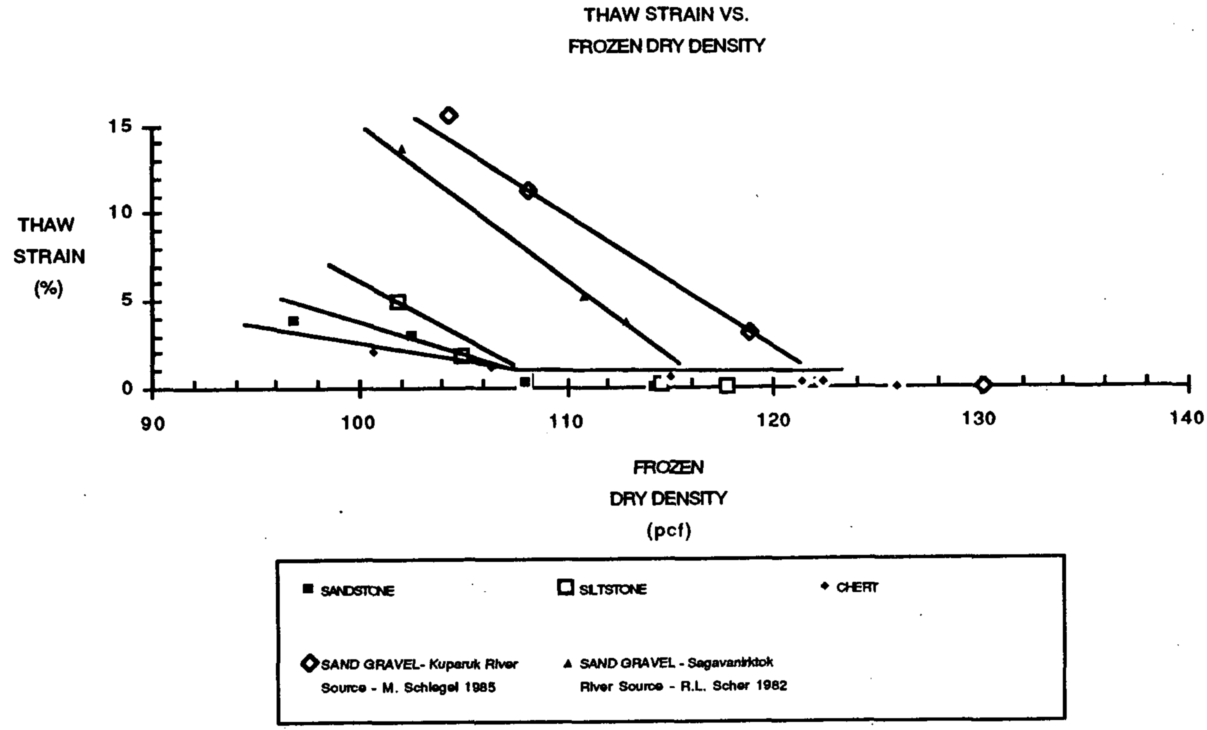

Figure 5. Thaw strain comparison.

Loading and hauling operations were facilitated in areas of low ice content. Areas with high ice content presented some trafficability and performance problems to the hauling and loading equipment. In these areas, ripping was required to break and separate the materials to improve equipment cycle times. Loading and hauling operations were facilitated by onsite coordination between the contractor and onsite geotechnical engineers and geologists. Due to the complex structure of the rock in the region and the variability associated with folding and faulting, geologic mapping of exposed excavations, onsite confirmation of use of blasted materials expedited drill and blast, fill and processing, and waste operations.

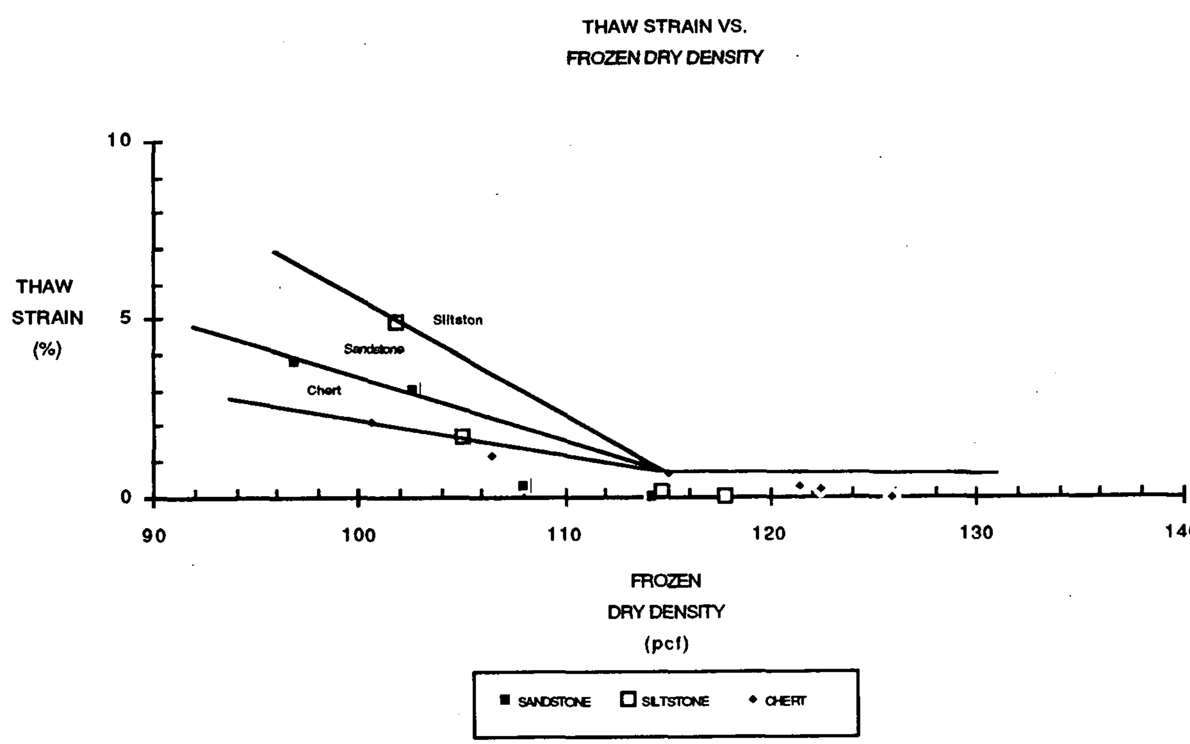

Figure 6. Thaw strain for processed rock fill.

Performance of the crushed in-place fill was observed to be dependent upon the durability of the rock and the amount of in-situ ice. The coarse rock fills, used for road base and major fill construction, were produced from drill and blast operations. Placement of the coarse blasted rock in fill sections in controlled lifts was dictated by the maximum particle size produced from the quarry operations (Fig. 7). Compaction of the coarse rock by vibratory static drum provided little densification and most of the compaction came from wheel traffic over the lift. Similarly, Huculak *et al.* (1978) reported that compaction of processed rock, used for the construction of the Dempster highway embankment fill in Northwestern Canada, was obtained by normal construction traffic, and compaction equipment was used only during placement of crushed road surfacing.

Quality control testing of the coarse in-place fill indicated densities of the coarse road embankment fill ranged from 131 to 148 pcf, dependent on the maximum size of the particles. Conventional laboratory moisture-density relationships by Modified Proctor could not readily be used as a guide for construction placement because of the coarse nature of the fills. (Fig. 8) Maximum-minimum density correlations were required to evaluate the coarse fill performance. Field in-place density testing was performed by nuclear methods in all the processed rock fill sections.

The road experienced substantial construction related traffic during the first spring after winter construction. Settlements in the winter placed fill sections were more obvious than in the fills placed during the previous summer season. Settlement along the road alignment was discontinuous, producing a washboard effect. The sections with adverse performance could be attributed to the lithology and percentage of natural moisture (ice) content in the rock. "Soft" rocks or those with higher ice contents reduced blasting efficiencies and produced oversized rock that caused lift thicknesses to increase. This minimized the amount of compaction or densification that would be achieved by wheel traffic or vibratory drum compactor, increasing the tendencies of the fill to bridge. Higher percentages of ice resulted in lower frozen densities and consequently greater settlement occurred on first time thaw.

Settlements in the road alignment due to compression of the organic mat and thaw of the subgrade soil was observed progressively during the summer. Initial observations of the varying rock fill materials was observed in the upland section of the road alignment where surface and residual soils over bedrock were of minimal thickness.

The rock materials used for road surfacing, structural fills for foundations, and concrete were processed to grain sizes acceptable for standard laboratory testing procedures. The observed performance of the processed rock was dependent on the durability of the rock source. The material sources selected for processing consisted of "hard" rock sources, primarily chert and sandstone. Performance observations of processed fills were similar to that used for conventional fill placement. Moisture-density relationships determined by Modified Proctor were used for construction placement quality control.

Maximum dry densities determined in the laboratory for the chert sources averaged 140 pcf and observed in the fill to range from 140 to 144 pcf. The sandstone averaged 144 pcf in laboratory testing and the fill ranged from 144 pcf to 148 pcf. The slightly lower density of the chert materials when compared to the sandstone could be attributed to the squared, blocky nature of the chert particles. This characteristic resulted in an open, porous embankment.

The performance of the processed rock was best observed during road surfacing activities. Crushing and

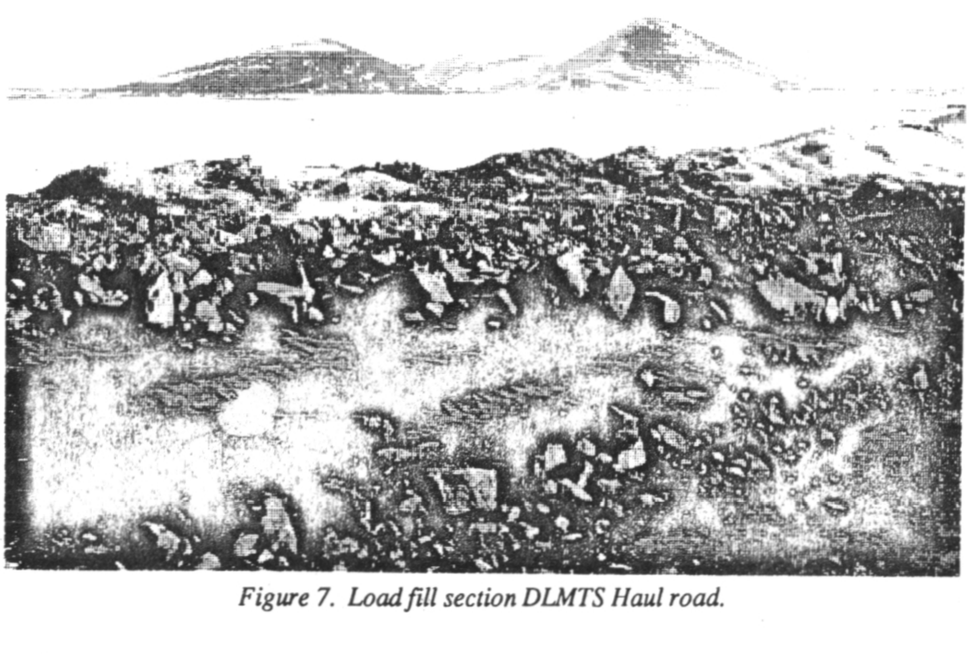

Figure 7. Load fill section DLMTS Haul road.

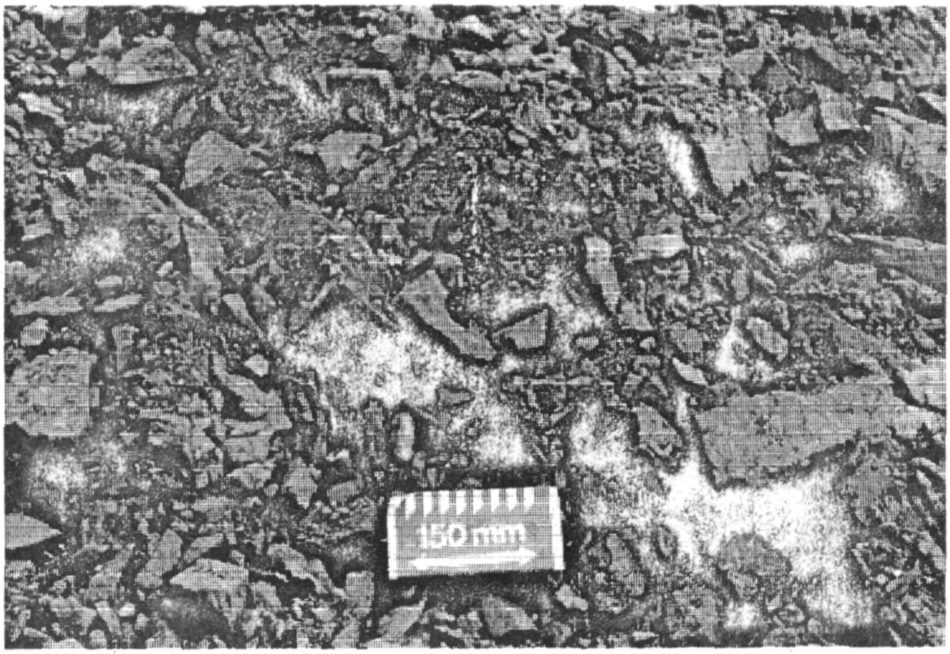

Figure 8. Typical rock fill DMTS.

processing experienced difficulties with meeting specified gradations. Gradations of the road surfacing were generally coarser than that specified. The observed performance of the sandstone during construction produced a more favorable material primarily due to the limited degradation associated with its placement. The finer material produced during handling and placement of the processed sandstone served as a "binder" in the fill section. The crushed chert, typically angular and blocky, did not contain sufficient fines to act as a binder and consequently the fill section "unravelled" or segregated.

Summary

Laboratory testing programs and construction observations have been performed to date during the construction of the Red Dog Facilities. Post construction monitoring and observations of the performance of the placed rock materials in engineered fill sections will be important. The continuing observations will provide valuable data for future use of processed rock and determining the critical parameters for designating the materials' applicable use in construction.

In summary, initial observations from laboratory studies and construction surveillance indicate that the lithology and *in-situ* ice contents of a permafrost rock source are key criteria in reviewing a source for use in civil construction projects. Placement performance of the rock materials is dictated by the maximum particle size. As particle sizes increase the placement lift thicknesses must also, therefore decreasing the effectiveness of conventional compaction equipment. Acceptable bedrock sources crushed to specified gradations for use as engineered fill can produce minimal thaw strains in comparison to natural deposits of sand and gravel. However long term performance is dependent on the in-place material's durability. This is an important consideration in selection of materials for use in shallow building and road foundations. Detailed site investigations adapted to the anticipated subsurface conditions of the project area are crucial in providing reliable on-site results, and the high quality samples necessary to perform the laboratory testing to complete these evaluations.

Future research needs:

- Develop maximum-minimum density relationships for coarse aggregate fill and additional quality assurance testing methods,
- Evaluate current material testing standards and develop adjustments to accommodate frozen placement,
- Provide interaction between private industry and State and Federal agencies to modify and expand accepted standards.

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