Compressive strength and tensile strength of rocks at sub-zero temperature

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The present paper deals with the uniaxial compressive and tensile behaviour of Chunar sandstone and Makrana marble at sub-zero temperature (0°C to -20°C) in dry and wet conditions. It was found that uniaxial compressive and tensile strengths of these rocks increased with decrease in temperature below 0°C. Both strengths in general and tensile strengths in particular of wet rocks increased more rapidly in comparison to dry rocks.

Tunnels and underground caverns are integral parts of any hydel power projects. Some of India’s hydel power projects are located in Himalayan region where temperature below 0°C is quite common. Also defence deployment in cold mountainous regions, i.e., Jammu & Kashmir, Himachal Pradesh, some part of Uttar Pradesh and North-East part of India, require large excavations for various purposes such as underground air-bases, underground missile and ammunition stations, deep trenches for protection against enemy.

On the other hand, availability of rich ore deposits in Himalaya and gradual depletion of ore reserves in plane area is compelling our country to do mining in Himalayan region to meet the demand of mineral resources.

In developed countries, scarcity of land in plane areas are forcing those countries to consider construction of laboratories, store houses, air bases, nuclear disposal chambers. in hilly areas (sub-zero temperature region). Japan is considering the construction of underground chambers for the storage of liquified natural gas due to problem of land.

The basic knowledge of physico-mechanical properties of rock, in sub-zero temperature range, is essential for efficient rock excavation and assessing the stability of the tunnels and rock caverns in cold regions.

Out of numerous physico-mechanical properties of rocks, the knowledge of strength properties (compressive, tensile and shear strength) are more important for safe design of rock structures. Therefore, the present investigation is carried out to determine the uniaxial compressive strength and tensile strength of Chunar sandstone and Makrana marble at sub-zero temperatures and to observe variation in rock strength with temperature (below 0°C).

The Chunar sandstone and Makrana marble were selected for the present investigation due to their homogeneous composition and isotropic strength behaviour.

**Experimental Procedure**

**Preparation of specimen**—Cylinders of 50mm diameter and 125mm length and discs of 50mm diameter and 25mm thickness were prepared from the same rock block for uniaxial compression test and Brazilian tensile test respectively. Rock cores, which were used for preparing cylindrical and disc specimens, were obtained by using NX size (54mm) diamond drill bit. Specimens were prepared in accordance with ISRM specifications.

The specimens were treated in following different ways:

(i) Twenty (ten cylindrical and ten disc specimens) specimens each of Chunar sandstone and Makrana marble were dried in oven at 105±5°C for four days. These were termed as dry specimens. The specimens were dried only for four days because after that there was no further loss in weight of the specimens.

(ii) The same number of specimens were submerged in water for only 7 days because after
that there was no increase in the weight of the specimens.

Specimens of both type (dry and wet) wrapped in polythene, were kept in deep freezer at -20°C temperature for 10 days. The specimens were wrapped in polythene for protecting the specimens from any loss of moisture.

**Determination of moisture content**—For determining moisture content of the specimens (dry or wet), some specimens of the set were ground (pulverized) in a ball mill. To minimise the possible moisture loss in the ball mill, minimum possible number of balls were used in the ball mill. 100 g of the ground material was kept in oven at 105+ 5°C temperature for 24 h. The % of moisture content was calculated by using the following formula:

\[
\text{Moisture content of material} = \frac{(100 - w)}{w} \times 100
\]

where, \(w\) = weight of the material after oven heating, g.

The moisture content of dry and wet Chunar sandstone were found to be 0.35% and 1.25% respectively whereas moisture content of dry and wet Makrana marble were 0.2% and 0.65% respectively.

**Low temperature arrangement**—A cubical case of 20cm size, made of 6mm thick perspex sheet and open at two opposite ends, was fabricated in the departmental workshop. It served as a low temperature chamber for the specimen during test (Fig. 1).

A special thermometer of temperature range -20°C to 150°C was used for temperature measurement. For facilitating the measurement of temperature just before the loading of specimen, a hole of 5mm dia was provided in one side of cubical case for inserting the thermometer.

**Testing procedure**—The cubical casing, filled with the mixture of ice and salts (sodium chloride and calcium chloride), was kept at the lower platen of the universal testing machine (UTM) of 40 tons compressional load capacity. The specimen was kept at the center of the lower platen and inside the casing (Fig. 2). The mixture of ice and salts was used to maintain the low temperature of the specimen during the experiment. The upper platen was brought in contact with the specimen and load was gradually applied at the rate of 0.5 MPa/s and 200 kN/s for uniaxial compression test and Brazilian tensile test respectively (as per the suggestion of ISRM) till the specimen fails.

The temperature of the specimen was measured by keeping the bulb of the thermometer in contact with the specimen for five minutes.

**Determination of compressive and tensile strengths of rock**—The uniaxial compressive strength of the rock specimen was calculated by the following formula:

\[
\sigma_c = \frac{P}{A} \quad \ldots \quad (1)
\]

where, \(\sigma_c\) = compressive strength, MPa,

\(P\) = failure load in uniaxial compression test, N and

\(A\) = initial cross-sectional area of the specimen, \(\text{mm}^2\).

The tensile strength of the specimen was calculated by using the following formula:

![Fig. 1—Low temperature chamber of perspex sheet](image)

![Fig. 2—Uniaxial compressional loading at sub-zero temperature](image)
\[ \sigma_t = \frac{2P}{\pi D t} \]  \tag{2}  

\( \sigma_t \) = tensile strength of the specimen, MPa,  
\( P \) = failure load in Brazilian test, N,  
\( D \) = diameter of the specimen, mm, and  
\( t \) = thickness of the specimen, mm.

Results and Discussion

Compressive strength—The variation in compressive strength with temperature are shown in Figs 3 and 4 for Chunar sandstone and Makrana sandstone.
marble respectively. It is quite evident from Figs 3 and 4 that compressive strength increased with decrease in temperature. The following reasons can be attributed to this phenomenon; as the temperature of the specimen was reduced, mineral grains of rock shrunk. This shrinkage of mineral grains produced tri-axial stress condition in the specimen which resulted in higher compressive strength. Also, the pore water became ice below 0°C and strength of this ice increased with decrease in temperature. Consequently, the strength of rocks increased with decrease in temperature.

It is also evident from Figs 3 and 4 that compressive strength of wet specimen was lower than dry specimen of same type of rocks at any particular sub-zero temperature. This lowering of wet rock strength may have resulted due to enlargement and extension of micro-cracks present in the rock specimen at the time of cooling. The intensity of enlargement and extension of micro-cracks depends on pore water % of the rock specimen. Since more pore water was present in wet specimen than in dry specimen, enlargement and extension was more in case of wet specimen. This resulted in lower compressive strength for wet specimen.

**Tensile strength**—The variation of tensile strength with temperature for Chunar sandstone and Makrana marble are shown in Figs 5 and 6 respectively. It is obvious from figures that tensile strength increased with decrease in temperature.

![Fig.5—Tensile strength of Chunar sandstone at sub-zero temperature](image)

![Fig.6—Tensile strength of Makrana marble at sub-zero temperature](image)
strength increased with decrease in temperature. The same reason can be extended from this phenomenon as was given in case of compressive strength.

It can also be seen from Figs 5 and 6 that initially tensile strength of the wet specimen was less than that of dry specimen of same rock but below -15°C, tensile strength of wet specimen exceeded that of dry specimen. We can consider following reasons behind this phenomenon: as the temperature dropped below 0°C, pore water changed into ice. The strength of ice increased with decrease in temperature below 0°C.

The compressive strength of ice, i.e., 1.08 to 1.96 MPa at 0°C and 3.92 to 8.04 MPa at -50°C was quite less in comparison to compressive strength of the rocks tested. But tensile strength of ice, i.e., 1.37 MPa at 0°C and 2.45 MPa at -50°C is quite near to tensile strength of rocks tested. Therefore, it can be said that ice contributed to the tensile strength but not to the uniaxial compressive strength of rocks. Besides this, ice also acted as an adhesive material and contributed to the tensile strength of the rocks.

As ice content of the wet specimen is more than dry specimen of the same rock, the tensile strength of wet specimen increased at a faster rate with decrease in temperature than that of dry specimen and exceeded the tensile strength of dry specimen below -15°C.

Fracture patterns observed during uniaxial compression test (Figs 7 and 8) and Brazilian tensile test (Figs 9 and 10) were same as a fracture patterns observed at the normal temperature (25°C).

Conclusions
Following important conclusions can be drawn from the present study:
(i) The compressive strength of both rocks (Chunar sandstone and Makrana marble) increased with decrease in temperature.
(ii) The compressive strength of the wet specimen was less than that of dry specimen for both types of rock.
(iii) The tensile strength of both rocks increased with decrease in temperature.
(iv) Initially, the tensile strength of the wet specimen was less than that of dry specimen of the same rock but it became more below $-15^\circ$C.
(v) Compressive and tensile strengths of Makrana marble were higher than those of Chunar sandstone.

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