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Relationship between flexural strength and compressive strength in concrete and ice

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ABSTRACT: Ice is a locally available material in cold regions, where it is used in temporary constructions and permanent hydraulic structures. Thus, it is of practical interest the introduction of a model capable of computing the flexural tensile strength of ice as function of its compressive strength. Accordingly, three point bending test and compression test have been performed for the first time on the same ice prism (40 × 40 × 160 mm^3). In accordance with the testing procedure suggested by UNI EN 196 for cement-based mortars, compression loads are applied on the two halves of the specimens previously broken in bending. In this way, the ratio between the modulus of rupture and the compressive strength of ice can be measured. As a result, although the specific strengths of cement-based materials are higher than those of ice, the flexural/compressive strength ratio of ice is larger than that obtained in normal strength mortar.

1 INTRODUCTION

1.1 State of the art

The development of scientific researches to create new materials and operational technologies is an important task, especially in cold regions. In recent years, interest in ice has increased not only as a scientific research topic but also as a promising material for solving real problems in Civil Engineering, regarding temporary ice construction and permanent hydraulic structures[1].

Snow and ice have been used a construction material since ancient times[2], especially in countries with a polar environment. For instance, the climatic conditions of more than half of the Russian Federation's territory allow for the construction and operation of natural cooling ice and ice ground installations. In other countries such as Canada, Norway, Sweden, Finland, Switzerland, Austria, and Japan, during the winter season, the temperature remains steady and sub-zero, and ice structures can be built. As a consequence, experimental and theoretical aspects of ice study as a structural material have been studied since the middle of the 20th century[3].

Ice is a natural material without any waste which is locally available. It has a variety of applications, including the structural use. The role of ice and snow architecture for festivals and exhibitions has recently grown, and new applications in the construction of ice-based infrastructure in polar locations with all-year low temperatures can be explored[4]. These mostly low-tech structures have proven to be energy-efficient and altogether sustainable.

Nevertheless, there are several issues with the structural application of ice, such as weak strength, brittle failure, etc. This limits the application of ice and snow structures to some extent. Moreover, high temperatures make the structure unpredictable, making it difficult to ensure safety[5], and unsuitable for commercial use. High temperatures also increase the creep rate, reducing the structure's lifespan. Because of the low strength, a considerable shell thickness is required, resulting in a comparatively long construction time

The layer thickness could be drastically reduced by using fibers within the ice structure. Because the ice composite has a higher (tensile) strength, wider spans can be produced, as well as new forms[6]. The use of fibrous and mesh fillers from local natural raw materials, e.g., waste wood processing (wood pulp, sawdust, blotting paper, and bark), vegetal plants, and animals (sheep wool, pig hair), has not been deeply investigated. It is obvious that in the conditions of the North and the Arctic, which are remote from industrial centers, reinforcing fillers are materials of natural origin from local raw materials. Eventually, the durability of fiber-reinforced ice (FRI) structures seems to be an urgent task concerning the economy of all the Cold Regions.

FRI is a mixture of plain ice and fiber, in which the fibers are distributed in all directions unevenly. The addition of fiber improve grain cohesion. Additionally, the presence of the fiber significantly minimizes the stress concentration at the crack point, preventing the crack from expanding rapidly and greatly improving the ductility of the FRI. Fibers act as reinforcements in FRI materials, while ice acts as a matrix that is subjected to stress. Eventually, fibers in FRI greatly improves the deformation ability of the ice material and the strength of the plain ice.

Another important factor for ice structures is temperature. The effect of temperature on the mechanical properties can be addressed from a molecular standpoint. The activation energy within the molecule increases as the temperature rises, and the bonding force between the molecules weakens, resulting in a lower capacity at higher temperatures. The activation energy in the molecule drops as the ice temperature decreases, while the coupling force between the molecules grows, increasing the ice's strength[7, 8].

On the other hand, concrete is a well-known material for structural application. Concrete is the second-most-used substance in the world after water[9]. Concrete has relatively high compressive strength, but significantly lower tensile strength. The ratio between tensile strength and compressive strength is an important material property of concrete.

Considering the complexity, cost, and time-consuming nature of performing tensile tests, many researchers and building guidelines are interested to predict the tensile strength from compressive strength and their relationship in a simplified method with satisfactory accuracy[10, 11]. The tensile strength to compressive strength ratio is determined by the strength of the concrete. Thus, the higher the compressive strength, the higher the tensile strength, but the rate of tensile strength rise is of diminishing order. Concrete tensile strength is more vulnerable to incorrect curing than compressive strength. The value of this ratio is applicable in several situations[12, 13].

For the mechanical properties of ice composite materials, there are still some aspects that need to be improved from the point of view of the existing research. One of these concepts is the possible ratio between tensile strength and compressive strength. The results of this analysis are particularly important because no comprehensive information on the reliabilities of the relationships used in the current literature has been available.

1.2 Research significance

This study introduces a relationship between the ratio of tensile strength to compressive strength (f_t/f_c) of plain ice specimens, and the results are compared with f_t/f_c ratio of cement-based materials. To this aim, first the evaluation of flexural and compressive strengths of plain ice and mortars are measured by performing the test suggested by UNI EN 196[14].

2 EXPERIMENTAL ANALYSIS

An experimental campaign has been performed at Politecnico di Torino (Italy) on cement-based mortars and plain ice. In the next step the experimental procedure on cement-based mortars and ice will be described separately.

2.1 Material and specimens for cement-based mortar

Regarding the mortar specimens, each batch for three test specimens shall consist of (450 ± 2) g of cement, (1350 ± 5) g of sand, and (225 ± 1) g of water. Mixture properties is described in the Table 1.

Table 1. Composition of the mortar for three specimens is mentioned bellow.

Specimen	***cement*** *(g)*	***Water*** *(g)*	***Sand*** *(g)*
Concrete	*450 ± 2*	*225 ± 1*	*1350 ± 5*

The method of construction is the same as in standard two-stage concrete[15]:

1. Filling the formwork with inert materials. The mold was divided into three horizontal compartments (40*40*160 mm). Three specimens can be cast at the same time this way (Fig.1a).

2. Injecting the grout, which has been poured into each compartment like molten metal, as shown in Fig.1b.

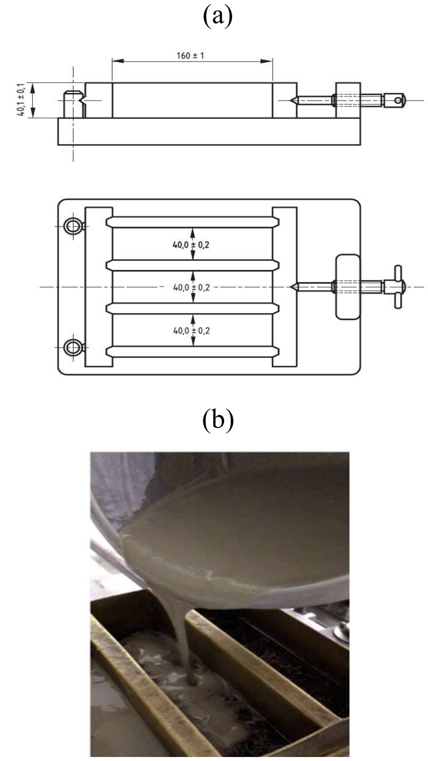


Figure 1– Casting two-stage cement-based materials: (a) geometrical properties of the mold; (b) Injecting grout

The properties of the specimens is mentioned in the following table.

Table 2.cement-based mortar specimens properties

Specimen	***Length*** *(mm)*	***Height*** *(mm)*	***Width*** *(mm)*	***Weight*** *Before test*	***Weight*** *After test*
Con-1	*160*	40.85	40.61	*1670*	*1670*
Con-2	*160*	40.64	40.64	*1670*	*1670*
Con-3	*160*	40.73	41.24	*1670*	*1670*

2.2 Experimental procedure

28 days after casting, all of the prisms were tested in three-point bending (see Fig. 2a) by applying the load P through a loading cell with a capacity of 100 kN. The displacement of the loading cell, whose stroke moved at a rate of 0.05 mm/min, was driven during the tests. Flexural testing separated the specimens into two halves, which were then compressed and tested. As illustrated in Fig. 2b, the load P is applied to a loading area of 40 x 40 mm in each half using a device with platens with a thickness of 10 mm. Until failure, the compressive force is gradually raised at a rate of 200 N per second.

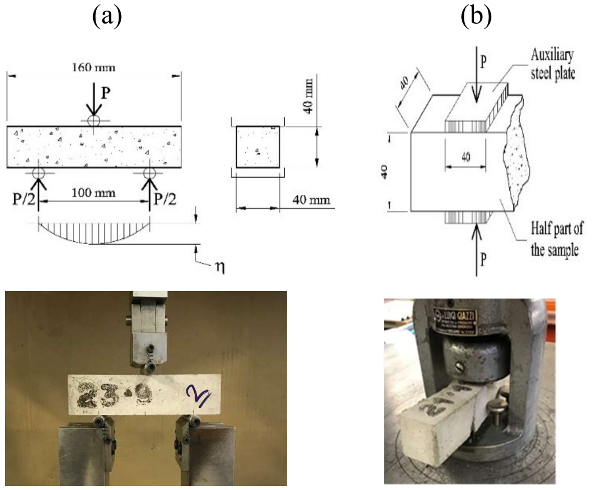


Figure 2–(a) Three-point bending tests for cementitious mortars[16]; (b) Compressive test for cementitious mortars

2.3 Experimental results

The applied force P (Fig.2a) and the mid-span deflection η were determined and reported. In Fig.3 we have the resulted curve for the cement-based mortar. The result of the test is represented in the next table. Having the result of flexural tests we can evaluate the flexural strength using the following equation.

$$\sigma = \frac{3FL}{2bd^2} \qquad (1)$$

Table 3. Result of flexural test on ice and mortar specimens

Specimen	**F$_{max}$** (N)	**Flexural strength*(F_u)*** *(MPa)*
Con-1	*2178.45*	*5.10*
Con-2	*2297.27*	*5.38*
Con-3	*2044.32*	*4.79*

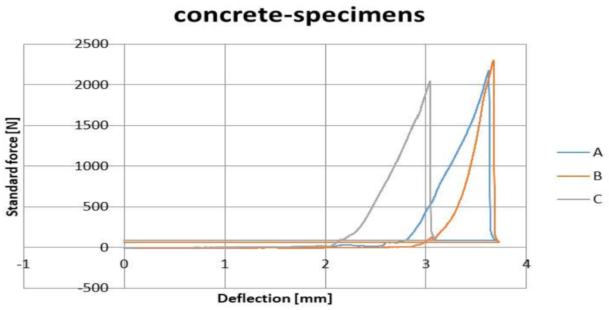


Figure 3– Load deflection diagram for cement-based mortar

Performing the 3PB test on each specimen we divide them and then we perform the compression tests on each half. The result of the test is represented in the next table.

Table 4. Result of compressive test on mortar specimens

Specimens	**d$_0$ (mm)**	**h$_0$ (mm)**	**F$_{max}$ (N)**	**F$_{u,max}$ (MPa)**
Con-1-A	*40*	*40*	*51103*	*31.93*
Con-1-B	*40*	*40*	*48739*	*30.46*
Con-2-A	*40*	*40*	*49071*	*30.66*
Con-2-B	*40*	*40*	*47692*	*29.8*
Con-3-A	*40*	*40*	*48371*	*30.23*
Con-3-B	*40*	*40*	*44969*	*28.1*

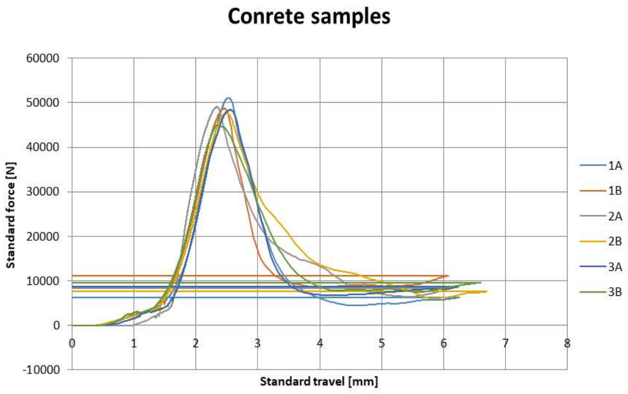


Figure 4– deflection-force diagrams concrete.

2.4 Material and specimens for Ice

Comparing to concrete samples, the main issue of ice specimens is their detachment from the mold. To tackle this issue we made a new mold from resin. The flexibility of this mold allows us to detach the ice specimens without distorting them.

After creating the mold, to test its functionality, we prepared a set of plane ice specimens. The size of the specimens is 40*40*160 (mm^3). The final result was quite good since the detachment was easy and the shape was acceptable. To evaluate the compressive and tensile strength we performed a set of 3PB and compression tests. This helps us to estimate the effectiveness of the machines while testing the ice and also compare the results with the reference data from Yue Wu's article[17].

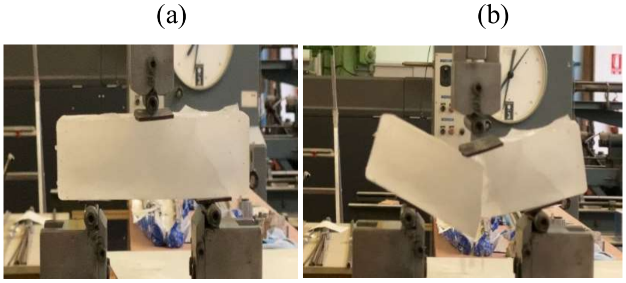
Figure 5– Resin mold and the plain ice specimen

Table 5. Ice specimen properties

Specimen	***Length*** *(mm)*	***Height*** *(mm)*	***Width*** *(mm)*	***Weight*** *Before test*	***Weight*** *After test*
Ice-1	*158.83*	*40.41*	*40.43*	*233g*	*232g*
Ice-2	*158.39*	*39.51*	*40.41*	*243g*	*241g*
Ice-3	*160.03*	*40.12*	*39.43*	*235g*	*232g*

2.5 Experimental procedure

For the evaluation of the flexural strength we performed a 3-point-bending test. Starting the test, first, we had the problem of specimen melting during the test process. For solving this issue, we increased the velocity of the test and also we put a set of rubber pieces on the contacted points of the machine and the ice specimens. The ice test was strain-control and the test velocity was 3mm/min for ice specimens. While for the mortar we applied the load at a rate of (50 ± 10) N/s.



(a) (b)

Figure 6– performing three-point-bending test on plane ice specimens (a): before the test (b): after the test

The result of the tests on ice is mentioned in the next part.

Table 6. Result of flexural test on ice and mortar specimens

Specimen	**F_{max}** (N)	**Flexural strength*(F_u)*** *(MPa)*
Ice-1	*455.89*	*1.06*
Ice-2	*373.33*	*0.87*
Ice-3	*368.48*	*0.86*

As we can see the flexural strengths of cement-based materials are higher than those of ice. On average the flexural strength of concrete is 5.5 times larger than ice. The deflection-force diagrams of the ice and concrete samples while performing 3PB-tests are represented below.

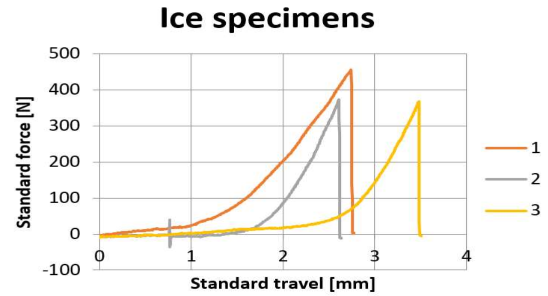
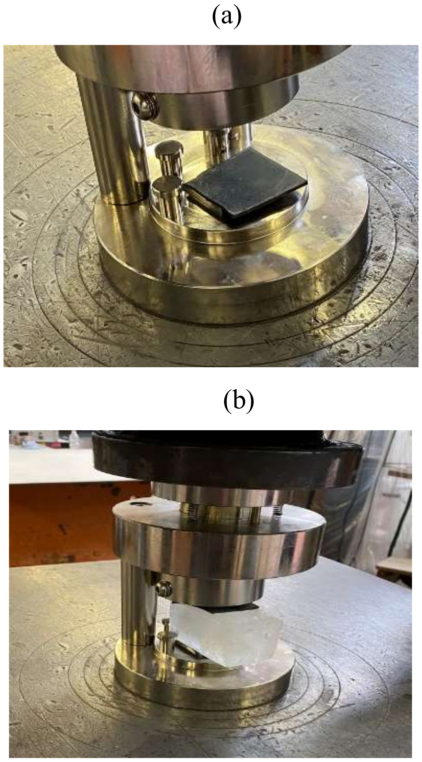


Figure 4– Force-deflection diagram of ice

Like the 3PB test, we put the rubber piece to prevent the issue of ice melting. We performed the tension control test and the velocity for the ice specimen is 30N/sec, while for the concrete specimen we imposed the load (2400 ± 200) N/s.



(a)

(b)

Figure 8– Compression test performed on ice (a): before the test (b): during the test.

The result of the test is represented in the next table. As we can see the compressive strengths of cement-based materials are higher than those of ice. On average the compressive strength of concrete is approximately 19 times larger than ice.

Table 7. Result of compressive test on ice specimens

Specimens	d_0 (mm)	h_0 (mm)	F_{max} (N)	$F_{u,max}$ (MPa)
Ice-1	*40*	*40*	*2214*	*1.38*
Ice-2	*40*	*40*	*3084*	*1.92*
Ice-3	*40*	*40*	*3400*	*2.12*
Ice-4	*40*	*40*	*2232*	*1.39*

The deflection-force diagrams of the ice and concrete samples while performing compression-tests are represented below.

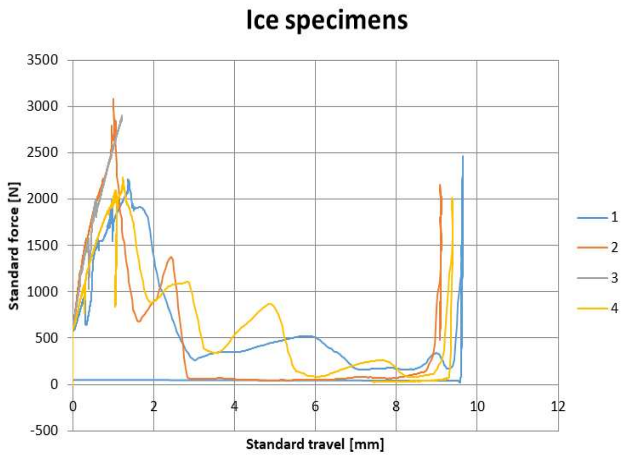


Figure 9– deflection-force diagrams ice.

3 ANALYSIS OF THE RESULTS

3.1 Comparing the data with literature

Comparing the result of the compression test with the literature, we see that our result regarding the plain ice is quite acceptable and close to the values from the Yue Wu's article. They performed the test in different temperatures and the compressive strength of the samples are improved when the temperature is decreased. Regarding the case of plain ice we have the following results. Our results needed to be compared with -5°C. The average of our test results is 1.70 Mpa

Table 8. Ice compressive strength evaluated in the article for different temperatures

fiber content	*Temperature(°C)*	*F_c(MPa)*
0	*-5*	*1.78*
0	*-10*	*2.59*
0	*-15*	*3.08*
0	*-20*	*3.4*

3.2 Ratio of tensile to compressive strength

The following evaluation is done to compare the behavior if ice and concrete, the latter defined according to euro-code 2 in the case of a concrete class C25/30. The flexural strength of concrete is defined as:

$$f_{ctm,fl} = \max\{(1.6\text{-h}/1000)\, f_{ctm}\ ;\ f_{ctm}\} \qquad (2)$$

Where, h=40 mm and the average direct tensile strength f_{ctm} has to be calculated with

$$f_{ctm} = 0.3 * f_{ck}^{(2/3)} <= \text{C50/60} \qquad (3)$$

In this formul, if $f_{ck} = 25$ MPa the flexural strength is $f_{ctmfl} = 4$ and the ratio $f_{ctmfl}/f_{cm} = 0.12$. On the contrary, in the case of ice, the ratio $f_{ctmfl}/f_{cm} = 0.51$, which is higher than that of concrete.

4 CONCLUSION

Eventually, even the flexural and compressive strengths of cement-based materials are significantly higher than those of ice, the flexural/compressive strength ratio of ice is larger than that obtained in normal strength mortar.

5 FURTHER RESEARCHES

In the next phase of our investigation, it is necessary to consider the effect of the temperature and also the addition of fibers to our ice specimens[17]. The results demonstrate that the strength of FRI is approximately four times that of plain ice, and its ductility is significantly greater than that of plain ice. The mechanical characteristics of FRI were temperature and fiber content sensitive.

On the other hand, ice is a temperature sensitive substance, and further research into the effect of temperature on the mechanical properties of ice material is required.

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