Strength of concrete at very low temperature

Prepared by:

Eng. Dana Yaseen Hama

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1. Introduction

Concrete has excellent structural performance even at very low temperature. It has been used for construction storage tanks such as for liquefied natural gas (boiling point of -162^{o}C) [1]. However, concrete may has some special properties when subjected to very low temperature, need to be understand sufficiently before using. Different properties of concrete subjected to temperature drop up to -180^{o}C have been investigated by the past researchers and there is useful information about the topic.

2. Aim of the study

The main goal behind this study is to highlight different mechanical properties of concrete and steel reinforcement in addition to deformations of the material subjected to very low temperatures exposure. The review has been made based on the published experimental works on structural concrete subjected to the extremely low temperature. This report is helpful to design concrete structural members intended to be used for cool product storage.

2. Concrete compressive strength

It is experimentally evidence that there is a compressive strength enhancement when concrete is subjected to a very low temperature [1,2,3,4]. This strength enhancement can be attributed to a formation of the ice in hydrated cement paste. Since, the freezing point of water is even less than the size pores are small, so that the absorbed water freezes at low temperatures [5]. Such as the ice can resist to the constraints, contrary that the water which it replaces, the frozen concrete has an extreme low effective porosity and therefore high strength. If the concrete is not exposed to lower temperatures, the pores are empty, so as the increase of the strength is low.

Cai et al. [4] concluded that at -35℃ the absolute growth values of compressive strength, flexural strength and splitting tensile strength decreased when strength grade increased.

Fig. 1 shows compressive strength variation with temperature drop for different moisture contents of concrete [*w*]. Strength enhancement due to temperature drop can be represented as [1]

$$\sigma_{CL} = \sigma_{CO} + \Delta\sigma_C \qquad (1)$$

in which $\Delta\sigma_C$ is nearly proportional to the moisture content of concrete (w). According to the results of Fig. 1, $\Delta\sigma_C$ increases as the temperature lowers up to -120 ^oC.

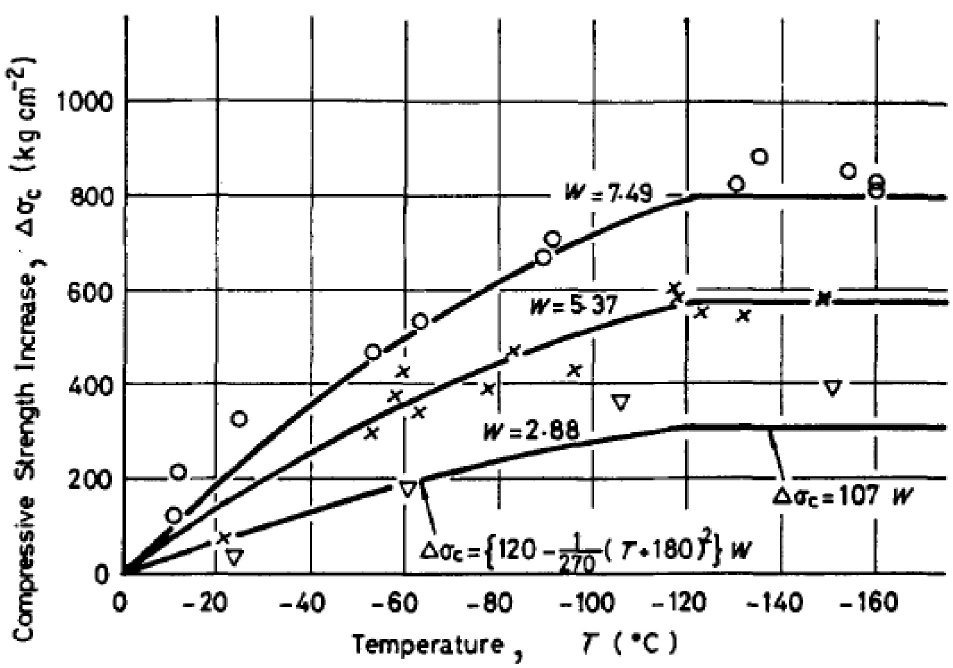

Fig. 1 Relations of compressive strength increase with temperature and moisture content. (o) Wet, average moisture content 7.49%, (x) air dry, 5.37%, (▽) oven-dried 15 h, 2.88%.

Fig. 2 shows one example of the relation between $\Delta\sigma_C$ and w at -160°C. One can observe that $\Delta\sigma_C$ is always in the same relationship with w, regardless of the concrete mix proportion.

Based on Fig. 2, for concrete subjected to temperature drop of -160°C, $\Delta\sigma_C$ is equal to $107w$, indicating a positive effect of moisture on the compressive strength enhancement. Based on this relation and Fig. 1, there is a chance to calculate compressive strength at any temperature if we know the control compressive strength (σ_{CO}) and moisture content (w).

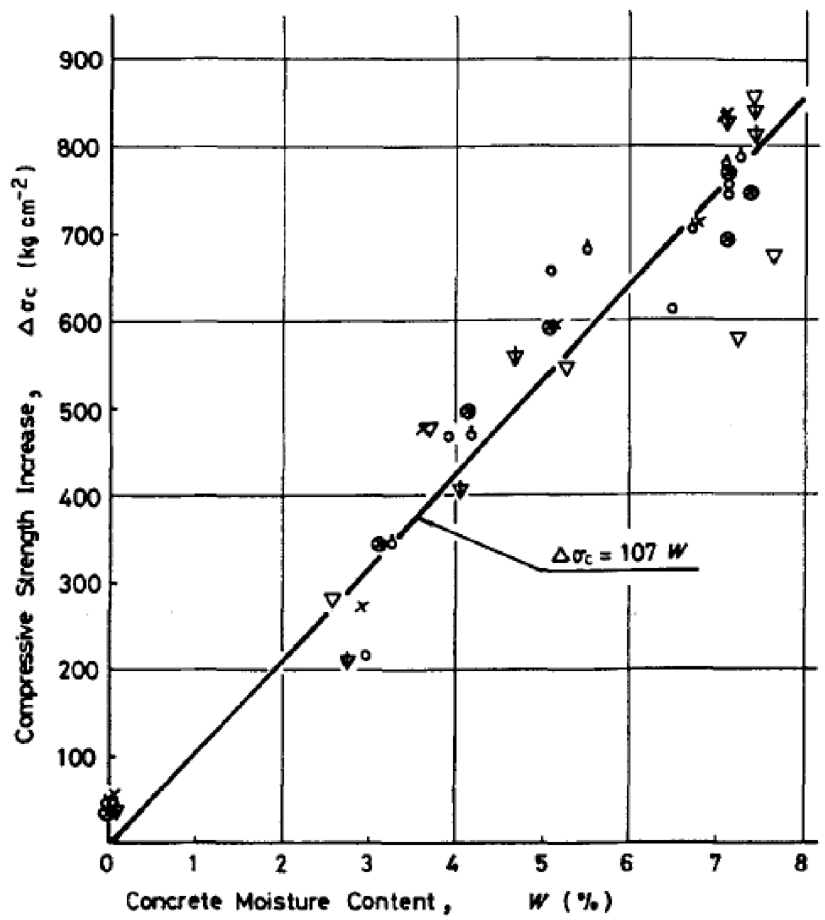

Fig. 2 Compressive strength increase at -160±10°C, (o) cement content 409 kg/m^3, w/c 0.45, (x) 368 lg/m^3, 0.5, (▽) 335 kg/m^3, 0.55, (ό)397 kg/m^3, 0.45, (⊗) 357 kg/m^3, 0.5, (▽̸) 325 kg/m^3, 0.55.

With regard to the effect of aggregate type, compressive strength enhancement was observed for different aggregates used in concrete mixes [6] (see Fig. 3).

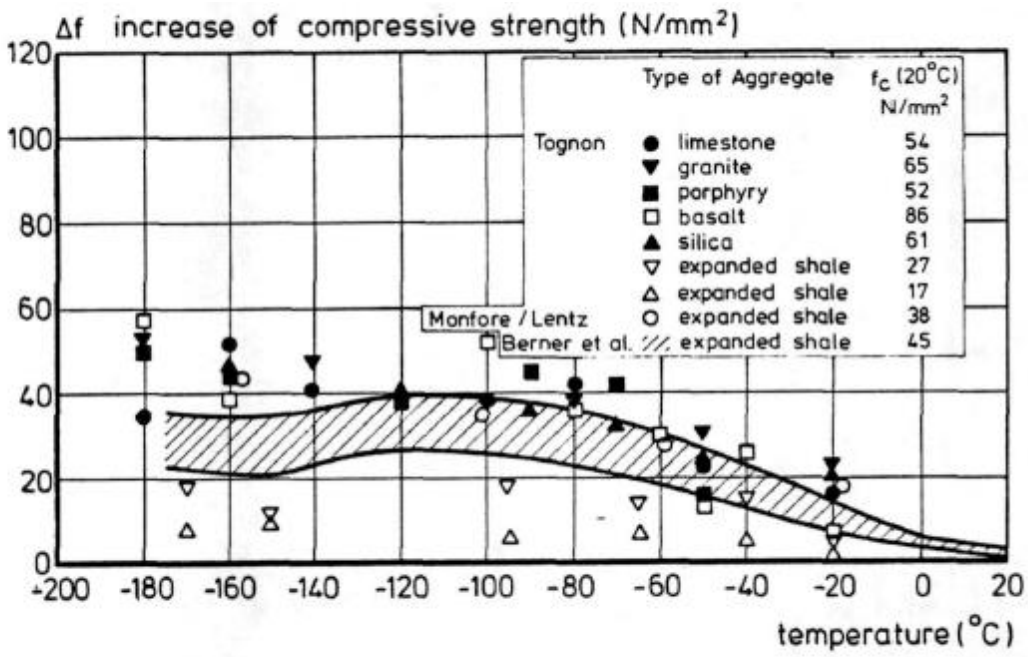

Fig. 3 The increase in compressive strength of concrete made with different aggregates versus temperature [6].

Proposed equations

Equations were proposed to determine the additional strength of concrete at low temperatures. Okada and Iguro [7] proposed Eq. 2, which is independent of the moisture content (*w)* and only depends on temperature (T). Goto and Miura [8] proposed Eq. 3, which is dependent on both the temperature and the moisture content, while Browne and Bamforth [9] have proposed Eq. 4, which is also a function of temperature and the moisture content.

$$f_c'(\mathrm{T}) = f_c'\,(20^{\circ}\mathrm{C}) + 5.3 - 0.84\,\mathrm{T} - 0.0027\,\mathrm{T}^2 \qquad (-10^{\circ}\mathrm{C} > \mathrm{T} > -100^{\circ}\mathrm{C}) \qquad (2)$$

$$f_c'(\mathrm{T}) = f_c'\,(20^{\circ}\mathrm{C}) - (2/15 + \mathrm{T}/2700)\,wT \qquad (0^{\circ}\mathrm{C} > \mathrm{T} > -120^{\circ}\mathrm{C}) \qquad (3)$$

$$f_c'(T) = f_c'(20^oC) - Tw/12 \qquad (0^oC > T > -120^oC) \qquad (4)$$

Fig. 4 evaluates these three equations with the data collected for partially dry concrete. One can observe that the equation proposed by Okada and Iguro [7] (Eq. 2) largely overpredicts the compressive strength in the range of temperature under consideration.

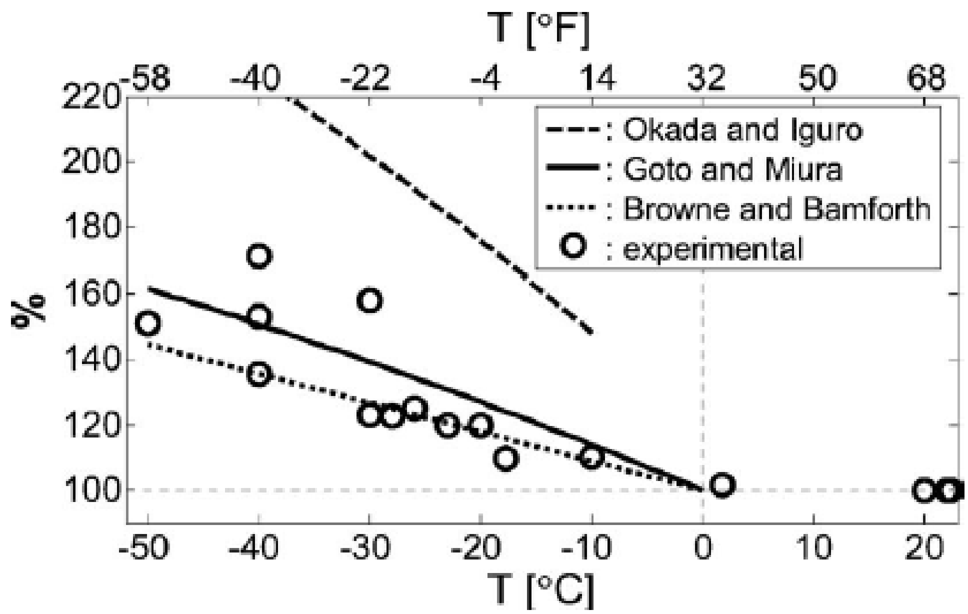

Fig. 4 Predictive equations for relative increase of concrete compressive strength at low temperatures (Data extracted from Nasser and Evans [10], Sehnal et al. [11], Filiatrault and Holleran [12], and Sloan [13].

3. Modulus of elasticity and Poisson's ratio

The effect of low temperatures on the concrete modulus of elasticity (*Ec*) can be observed in Fig. 5. There is a significant scatter in the data, however the trend shows that modulus of elasticity increases with decreasing temperatures. Nonetheless, the rate of increase in the modulus of elasticity has been found to be smaller than that for the compressive strength [2]. Fig. 6 shows modulus of elasticity variation versus temperature for normal and lightweight concretes [6], from which one can observe the elastic modulus enhancement with the temperature drop, but such enhancement is relatively low for lightweight concrete.

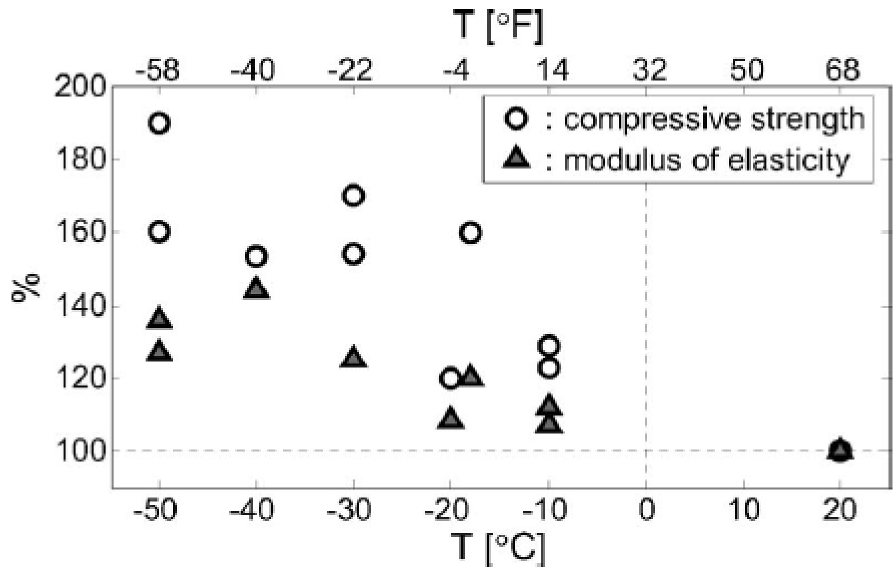

Fig. 5 Measured values of concrete modulus of elasticity and compressive strength versus temperature- expressed as a percentage of the values measured at 20°C (data extracted from Kasami et al. [14], Marshall [15], Lee et al. [16] and Filiatrault and Holleran [12]).

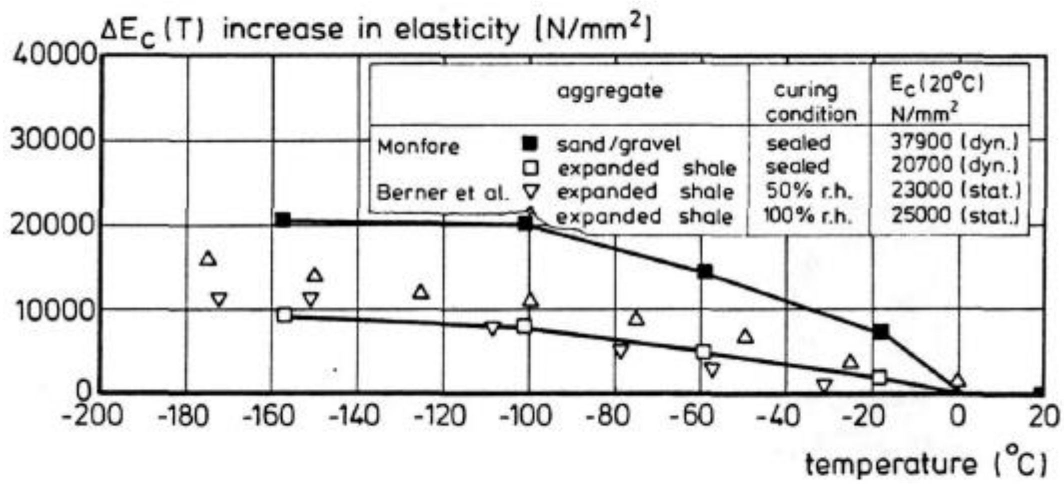

Fig. 6 Increase in modulus of elasticity versus temperature for normal and lightweight concrete [6]

Information regarding the influence of low temperatures on Poisson’s ratio of concrete is limited. Lee et al. [16] reported a linear increase in Poisson’s ratio as the temperature decreases below freezing. At −40°C, an increase of 40% was found, which is approximately the same increase as reported by Marshall [15]. In confined concrete such as in columns, this increase may cause the confining steel to rupture prematurely due to the added expansion of the confined concrete.

4. Stress- strain relationship

Similar to the compressive strength, the stress-strain behavior of concrete is highly influenced by the temperature and moisture of the specimens tested (see Fig. 7). It is noted that the concrete cylinder at −40°C failed abruptly without much softening after the maximum compressive stress is reached. Rostàsy and Wiedemann [17] showed how saturated concrete cooled at −170°C behaves in a purely elastic and brittle manner.

From their results (given in Fig. 8), it is noticed that the strain at maximum stress (ε_{co}) increases linearly when the temperature decreases below freezing and until −50°C where a maximum is attained. After this point, ε_{co} starts decreasing, and at −170°C, it reaches practically that measured at room temperature.

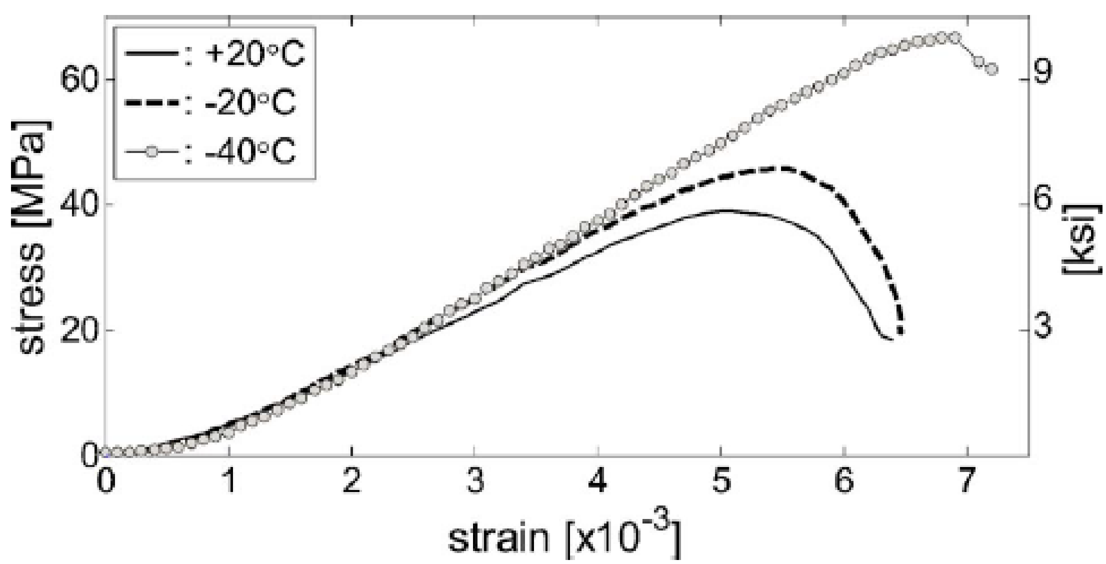

Fig. 7 Concrete stress-strain response at different temperatures (data from Sloan [13])

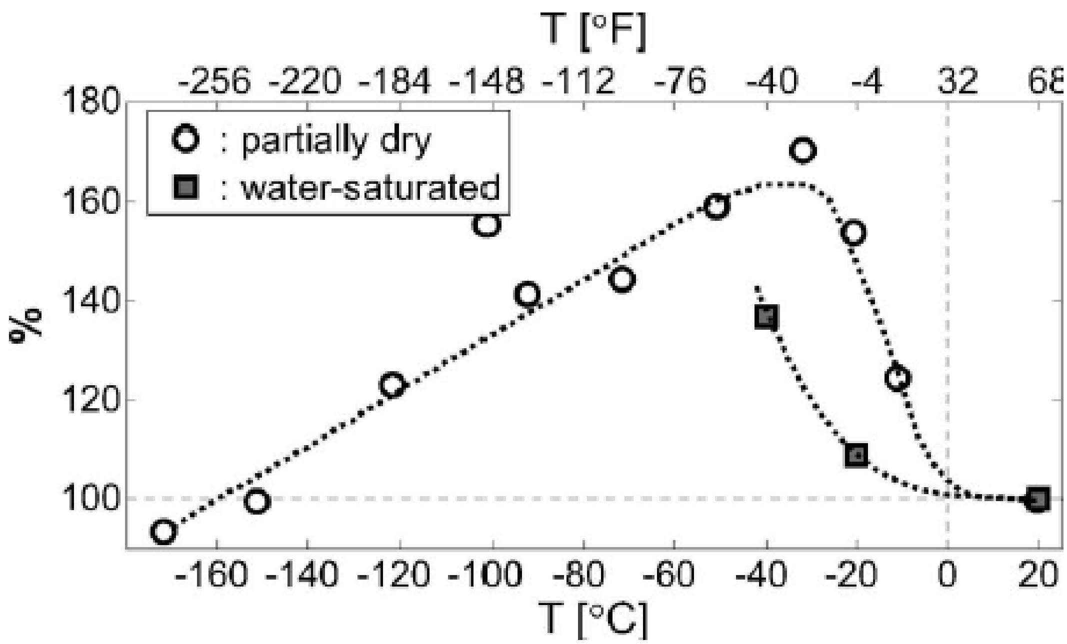

Fig. 8 Measured values of concrete strain at maximum stress versus tempreature expressed as a precentage of the values at 20°C (data extracted from Rostàsy and Wiedemann [17] and Sloan [13])

5. Tensile strength

Identical to the case of compressive strength, tensile strength also increases as the temperature falls. Fig. 9 shows the relation between compressive strength and tensile strength of concrete subjected to a very low temperature [1]. From this relationship one can estimate the tensile strength (σ_T) from the compressive strength (σ_c) as follows

$$\sigma_T = 0.38\,(\sigma_c)^{0.75} \qquad (5)$$

There is a chance to calculate the tensile strength of concrete at a given temperature (T) based on the compressive strength at a given temperature ($f_c'(T)$), tensile strength at normal temperature (f_t (20°C)) and compressive strength (f_c' (20°C)) at normal temperature, as follows [2]

$$\sigma_t(T) = (1 - 0.0105T)\, k_{1T} \sqrt{f_c'(T)} \quad (0^oC > T > -50^oC) \qquad (6)$$

In which

$$k_{1T} = \frac{f_t(20^oC)}{\sqrt{f_c'(20^oC)}}$$

Fig. 10 shows variation of splitting tensile strength of concrete made from different aggregates with temperature drop [6].

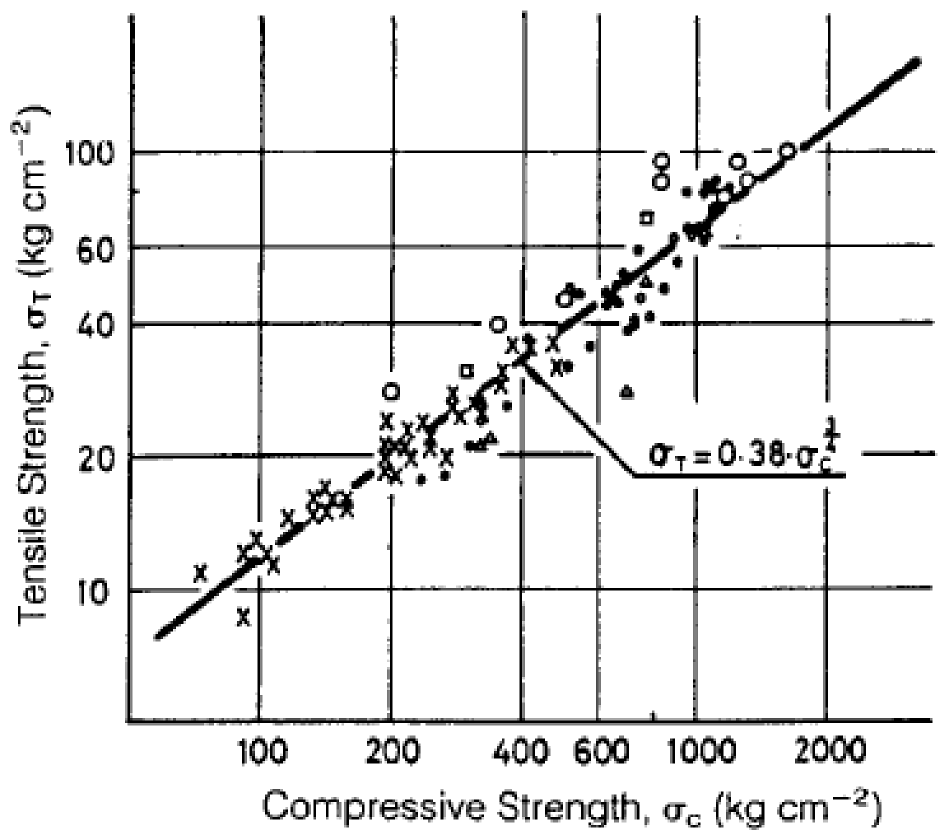

Fig. 9 Relation between tensile strength and compressive strength. (o) -160±10^{o}C, (x) normal temperature, (Δ)-100^{o}C, (□)-50^{o}C.

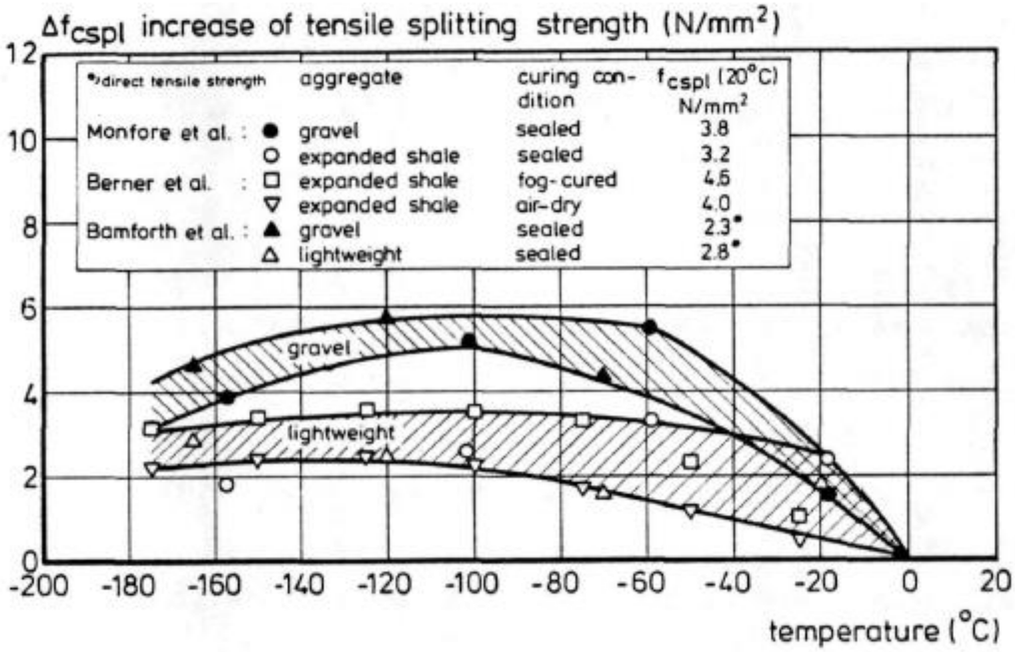

Fig. 10 Increase in tensile splitting strength with different aggregates versus temperature [6].

6. Deformations

Fig. 11 shows the variation of surface temperature and strain. As the coefficient of linear expansions are different between aggregate and mortar, some internal stresses are produced when the internal temperature is very low. This makes for a concrete to be hard and brittle at very low temperature, and is more easily influenced by the internal stress when it breaks [1].

Fig. 12 shows the relationships between the average temperatures and strains of concrete, mortar, cement paste and aggregate. From this figure we can understand that the strain hysteresis is due to the cement paste [1].

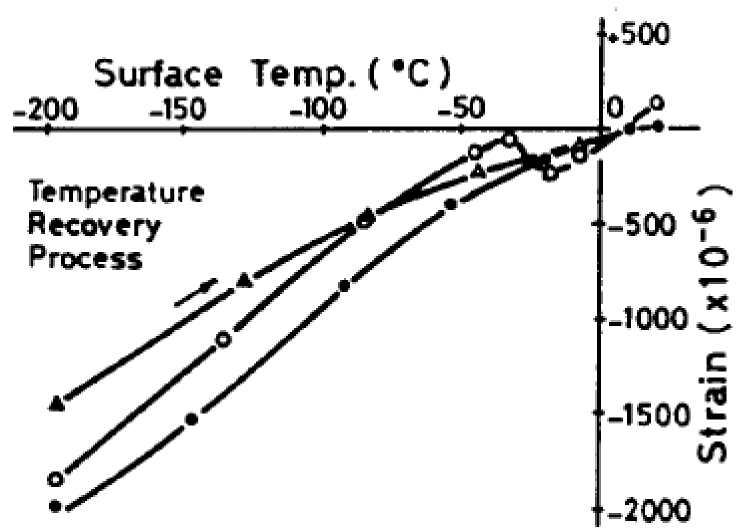

Fig. 11 Relation of shrinkage strain to surface temperature of mortar and aggregate. (o) Mortar, cured in water, (●) mortar, air-dried, (Δ) aggregate, cured in water. Insulating material thickness 2 mm.

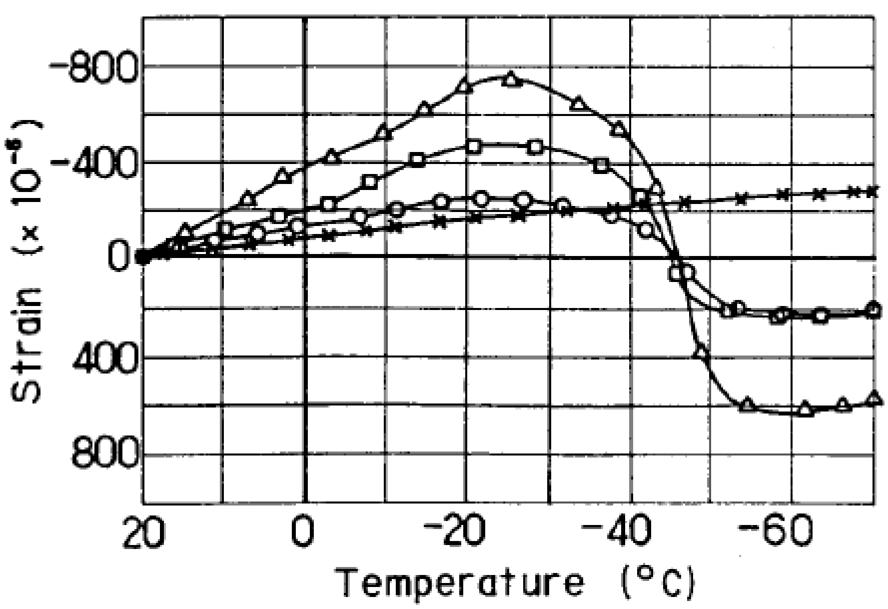

Fig. 12 Strains of (o) concrete, (□) mortar, (Δ) cement paste and (x) aggregate.

7- Cyclic Behavior

Results obtained by Berner et al. [5] indicate that the effect of low temperatures on concrete subjected to cyclic loads is the same as that for monotonic loads:

compressive strength and modulus of elasticity increase, though in a smaller proportion.

Fig. 13 shows the relation between the residual strain and the frequency of the cooling process when concrete specimens (w/c = 0.56) are repeatedly cooled with different minimum temperatures [1].

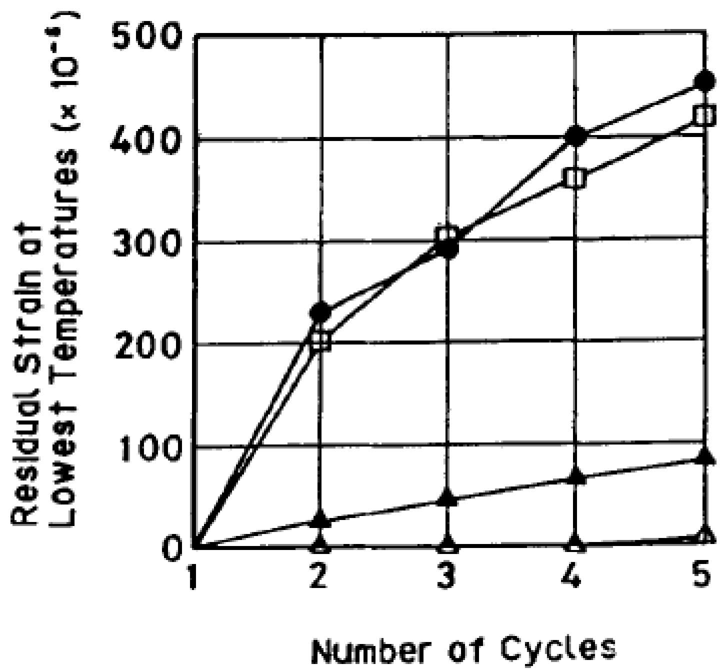

Fig. 13 Residual strain of concrete cooled to different temperatures: cyclic temperature range (●) +4 to -70°C, (□) +4 to -50°C, (▲)+4 to -30°C, (Δ) +4 to -20°C.

8. Concrete-Steel Bond Behavior

Concrete bond strength at low temperature has been investigated by Lee et al. [16,18] and Shih et al. [19] based on pullout tests of reinforcing bars embedded in normal and high strength concrete under monotonic, repeated cyclic, and reverse cyclic loadings. Results obtained show that local bond strength increases at low temperatures for all three loading conditions under investigation. This increase in bond strength is larger in normal strength concrete than in high strength concrete.

Variation of bond stress with temperature drop for different curing condition of concrete is given in Fig. 14.

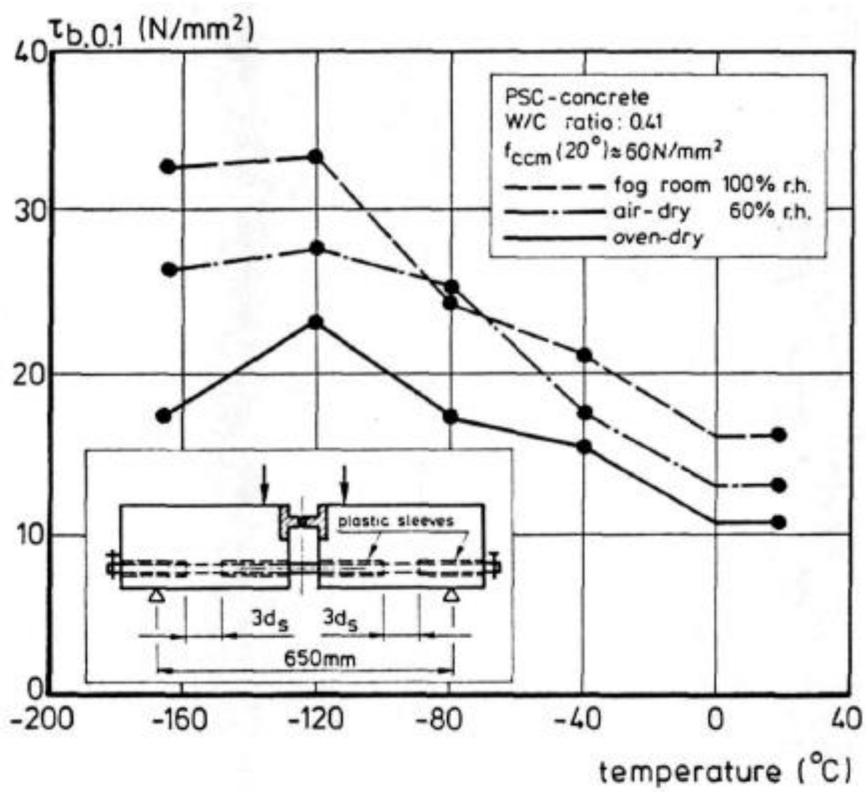

Fig. 14 Bond stress determined by means of a beam test at 0.1 mm slip for different curing conditions versus temperature [20]

9. Low Temperature Effects on Reinforcing Steel

Past research has indicated that, as temperature reduces, the yield and tensile strength of reinforcing steel bars increase [2]. Data presented in Fig. 15 correspond to bars tested at a strain rate of $0.001s{-}1$, shows that the increase in yield strength is slightly larger than the increase in tensile strength. Both can be approximated to be about 10–12% in the temperature range of −40°C to −25°C and then linearly decreasing to zero at 0°C. Results obtained by Elices et al. [21] show an increase of 80% and 36% in the yielding and tensile strength, respectively, of reinforcing bars tested at −180°C. The referenced investigations and material testing from this project (see Fig. 16) indicate that neither the modulus of elasticity nor the ductility of the specimens are significantly affected at temperatures above −30°C. According to Elices et al. [21], cold temperatures significantly reduce the ultimate strain only when the bar has surface defects such as cuts or notches.

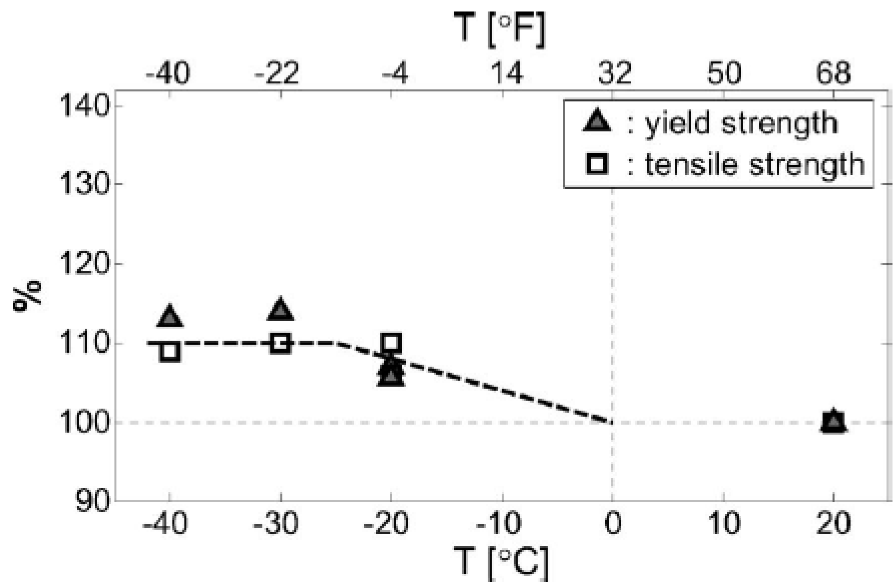

Fig. 15 Measured values of yield and tensile strengths of steel reinforcing bars values versus temperature- expressed as a function of the values measured at 20^{o}C (data extracted from Filiatrault and Holleran [12] and Sloan [13])

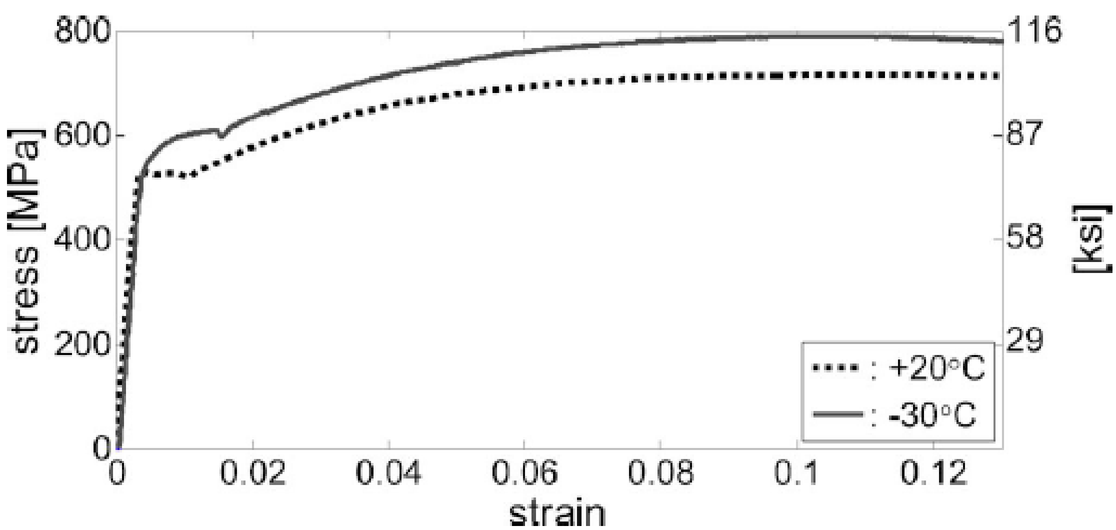

Fig. 16 Stress-strain behavior of steel reinforcing bars at low temperatures [13].

10. Conclusions

From this report study one concludes the following:

1- There is an increase of compressive strength of concrete subjected to drop in temperature up to -160^{o}C and the increase ratio enhanced with moisture content of concrete. Stress-strain relationship of concrete is also modified with temperature drop in which strain at peak stress increases and concrete tends to be more rigid.

2- There is a tensile strength and elastic modulus enhancement with temperature drop identical to the case of compressive strength. However, the enhancement ratio is lower for the case of lightweight concrete.

3- For concrete subjected to cyclic temperature range between +4^{o}C and -30^{o}C there is a very low residual strain, indicating low vulnerability to deterioration.

4- Yield stress of steel reinforcement and bond stress between concrete and steel rebar are increased with the temperature drop, while there is a negligible change of tensile stress-strain behavior of steel reinforcement.

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