A Two-stage Model for Complex Strain Behavior of Mortar under Freeze Thaw Cycles

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1. Introduction

In cold regions, frost action is a serious threat to the concrete structures. Once frost damage happens, deterioration process like chloride iron, carbon dioxide immigration and even the frost action itself will be largely accelerated, result in shorter service life. Frost damage is thought caused by the internal forces generated during freezing and thawing cycles. If the saturation degree is very high, the local tensile stress could be big enough to exceed the tensile strength of the material, then the irreversible cracks will occur, thus result in plastic tensile strain and residual strain even the temperature returns above 0^{o}C. As the number of freeze thaw cycles (FTC) increases, the peak strain and residual strain of each cycle could become bigger and bigger. But sometimes after several FTCs, the peak strain and residual strain would stop increasing, and start to decrease. This phenomenon is closely related to the moisture content and moisture distribution in the material. Especially for partially saturated specimens (saturation degree is lower than 90%), the expansion could be seldom observed, but the contraction domains. Therefore, it is obvious that both positive stress and negative stress will be applied on the pore wall during FTCs.

The frost damage is thought main caused by two effects: the moisture and the difference of the coefficient of thermal expansion (CTE) between cement and aggregates. Here for mortar, since the aggregate is very fine, so the effect of CTE can be neglected, only the forces caused by moisture will be taken into consideration. In the past study, the hydraulic pressure generated when ice forms inside the material was thought to be the main cause of damage. But according to some recent theories, the hydraulic pressure is significant only if the saturation degree is very high (because only a little water will freeze even at -20^{o}C), or if there is a sudden ice formation, otherwise the hydraulic pressure can be avoided. Scherer (2005) discussed the crystallization phenomenon in pores using thermodynamic theory, stated and proved that there is another positive pressure “crystallization pressure”, which is always accompanied with negative water pressure. And these two effects are the reasons for expansion and contraction observed in many experiments, even though the specimen is partially saturated so that the hydraulic pressure can be avoided.

So in this paper, the hydraulic pressure, crystallization pressure and the negative pore water pressure will be all taken into consideration to explain the complex strain behavior of the mortar under freeze thaw cycles. Some experimental results will also be used to verify the proposed model qualitatively and quantitatively.

2. Experimental Observation

In the authors’ experiment, the mortar specimens were made using ordinary Portland cement with density of 3.14 g/cm3, fine aggregate which is 1.2mm or less in size with density of 2.67 g/cm3, without air entraining agent to promote damage. After curing, specimens were cut into size of 40mm x 40mm x 2mm. Specimens were submerged underwater until mass was constant to attain full saturation. Finally, the specimens were sealed with vinyl tape to prevent water uptake or loss. Thus the specimens can be regarded as “fully saturated” (actually some pores are still empty, compared to the vacuum saturated cases, water saturated specimens just have nearly 90% of pore volume occupied by water). And also the total moisture content is constant because they have been sealed. Since the specimens are very thin, so it can also be regards as an uniform temperature field. The temperature history of one FTC is (Fig.1):

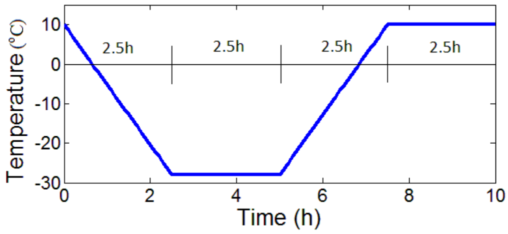
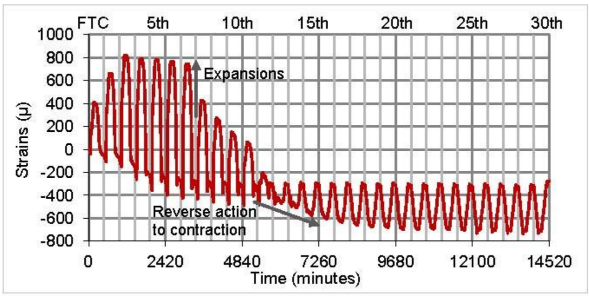
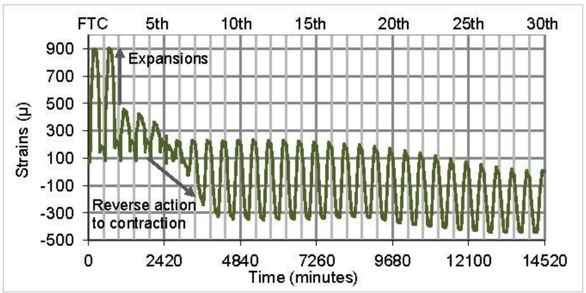


Fig. 1 Temperature history of one freezing and thawing cycle

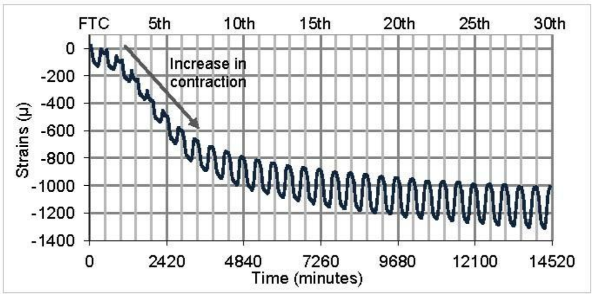
During the test, different strain behaviors have been observed. It can be seen that the overall tendency is first expansion and then contraction. But for each particular case, the lasting period of expansion is different (Fig. 2(a) and 2(b)). And sometimes there is even no expansion, but only contraction from the beginning (Fig. 2(c)). If the damage is evaluated simply by the plastic tensile strain (Mutikn et al), then it can be seen that w/c ratio of 0.7 and 0.5 has little damage while the damage of w/c ratio of 0.3 is significant. In common sense, the damage caused by frost action contains two parts: the moisture condition and the deterioration of the material itself. For the moisture part, three kinds of internal forces (hydraulic pressure, crystallization pressure and negative water pressure) will vary according to the moisture condition. And for the mechanical properties of the material, there is plastic tensile strain if the local stress exceeds the tensile strength, and also there is residual shrinkage due to the effect of creep. In order to avoid the coupling problem of physical process and material properties, here these two issues are treated separately.



a)　70% W/C & Fine aggregate of 1090 kg/m^3



b)　50% W/C & Fine aggregate of 1090 kg/m^3



c)　30% W/C & Fine aggregate of 755 kg/m^3

Fig. 2 Strain behavior observed in experiment

3. Two-stage Model

Other than the material deterioration (residual strain), it can also be seen from Fig. 2 that the internal forces have changed seriously. So here, a two-stage model is proposed to explain this phenomenon.

3.1 Basic Assumptions

◆ There are three kinds of pressures inside the cement-based material when suffering FTCs:

1) hydraulic pressure (caused by volume expansion of water from liquid to solid phase)
2) crystallization pressure (caused by the repulsive force between crystal and pore wall)
3) negative pore water pressure (caused by the super cooling liquid water)

◆ In general, the commonly known “fully saturated (water saturated)” specimens are not 100% saturated. A certain amount of small air bubbles are inevitably trapped in very small pores, the location of these bubbles will redistribute during FTCs, after several FTCs, a dynamic balance will be achieved.

◆ The hydraulic pressure is only significant before achieving the balance mentioned above, and after that, the hydraulic pressure can be neglected.

◆ The condition that before and after this balance is called “first stage” and “second stage” respectively (see Fig. 3).

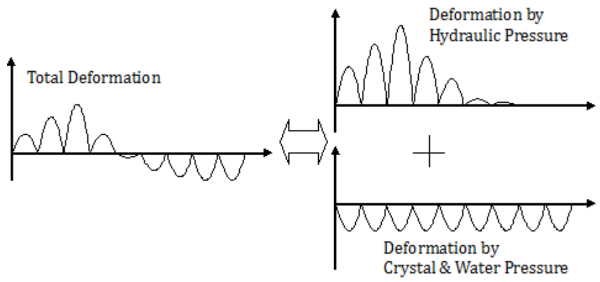


Fig. 3 Total deformation and the contribution of each force

3.2 First stage

This stage usually takes 3 to 8 FTCs, three kinds of pressure are all significant at this stage.

Hydraulic pressure σ_H

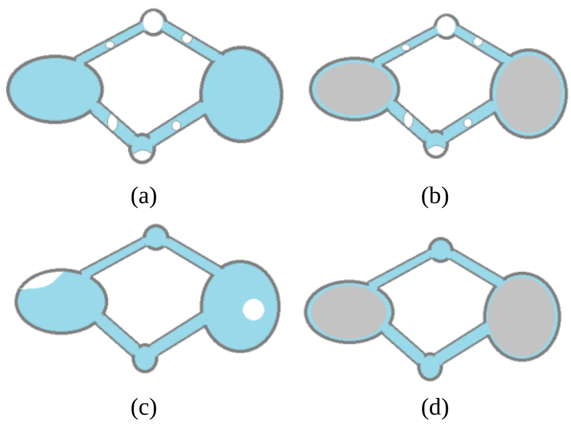


Fig. 4 Water redistribution

During first FTC, although there is still pore space to hold the additional volume when ice forms, the trapped air has no time to move to bigger pores before ice grows larger. So the hydraulic pressure will still generate. But as the time lapse, the trapped air will move to larger pores eventually (Fig. 4). This redistribution needs several FTCs, and finally, the air will stay in large pores. The hydraulic pressure will also decrease. The hydraulic pressure in this stage is usually difficult to evaluate, because it is closely related to the initial water distribution of the specimens. From the experimental results, this uncertainty can be also seen obviously.

Crystallization pressure σ_C

The crystallization pressure will be generated in the pores where ice formation happens, the value is:

$$\sigma_c = \frac{\gamma_{CL}}{r-\delta} \tag{1}$$

where $\gamma_{CL} \approx 0.04 J/m^2$ is the specific energy of the crystal/liquid interface, r is the radius of the pores where ice exists, and δ is the thickness of the liquid film between the crystal and the pore wall, for water, $\delta \approx 0.9nm$.

If given a certain temperature, the ice occupies the pores whose $r_{cl} < r < r_{cv}$, and if the pore density function is $v(r)$, then the equivalent crystallization pressure is (Fig. 5):

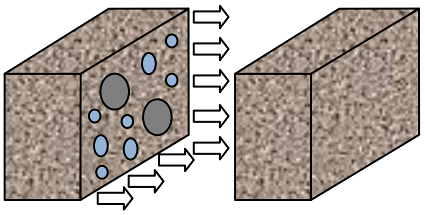


Fig. 5 Equivalent macro stress caused by stress in micro pores (two dimensional)

$$\sigma_C = \sigma_c(r_{cl})\left(\int_{r_{cl}}^{r_{cv}} v(r)dr\right)^{\frac{2}{3}} = \frac{\gamma_{CL}}{r_{cl}-\delta}(V(r_{cv})-V(r_{cl}))^{\frac{2}{3}} \tag{2}$$

where $V(r_0)=\int_{\delta}^{r_0} v(r)dr$ is the accumulated pore volume (percentage of the material's total volume). $V(r_{cv})-V(r_{cl})$ represents the volume that ice occupies.

Negative water pressure σ_L

Also based on the thermodynamic analysis, the super cooling liquid water can generate very big negative pressure, which is the reason of shrinkage. Since the degree of super cooling depends on the pore size, the negative water pressure can be written:

$$\sigma_l = -\frac{2\gamma_{CL}}{r-\delta} \tag{3}$$

The liquid phase occupies the pores whose $\delta < r < r_{cl}$, but the negative water pressure should exist in pores $\delta < r < r_{cv}$, so the equivalent negative water pressure is:

$$\sigma_L = \sigma_l(r_{cl})\left(\int_{\delta}^{r_{cv}} v(r)dr\right)^{\frac{2}{3}} = -\frac{2\gamma_{CL}}{r_{cl}-\delta}V(r_{cv})^{\frac{2}{3}} \tag{4}$$

In sum, during the first stage, the total stress applied on the material is:

$$\begin{aligned}\sigma &= \sigma_H + \sigma_C + \sigma_L \\ &= \sigma_H + \frac{\gamma_{CL}}{r_{cl}-\delta}(V(r_{cv})-V(r_{cl}))^{\frac{2}{3}} - \frac{2\gamma_{CL}}{r_{cl}-\delta}V(r_{cv})^{\frac{2}{3}}\end{aligned} \tag{5}$$

The total pressure calculated in Eq. (5) could be positive or negative, depending on the value of hydraulic pressure.

3.3 Second stage

The "second stage" means that the redistribution of trapped air bubble is stopped (sealed cases) or in dynamic balance (open cases). For commonly water saturated specimens, if compared to the vacuum treatment, the water can only cover 90% pore space. So if there is no additional moisture added in, even all of the 90% water forms into ice, the volume will just become 99% (90%*1.1). So the hydraulic pressure σ_H can be neglected. Then, the total stress is:

$$\begin{aligned}\sigma &= \sigma_C + \sigma_L \\ &= \frac{\gamma_{CL}}{r_{cl}-\delta}(V(r_{cv})-V(r_{cl}))^{\frac{2}{3}} - \frac{2\gamma_{CL}}{r_{cl}-\delta}V(r_{cv})^{\frac{2}{3}}\end{aligned} \tag{6}$$

This value will always be negative, that means, during the second stage, there is only shrinkage for any kinds of specimens with any kinds of environmental conditions.

4. Results and Discussions

Taking water saturated condition as an example, and the lowest temperature is -28°C. Since the hydraulic pressure is not possible to evaluate precisely and even the experiment results also have very big variation. So here we just compare the crystallization pressure and negative water pressure, then the only the second stage will be discussed.

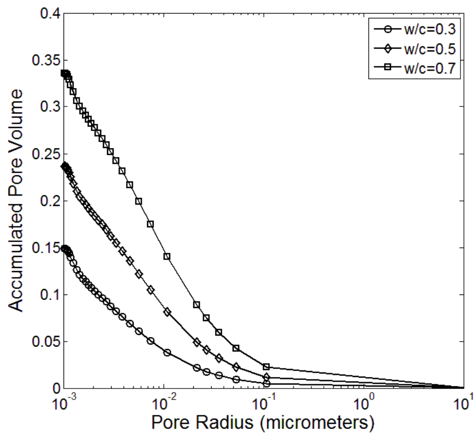


Fig. 6 Empirical pore size distribution

The pore size distribution is using an empirical formula developed by Gong et al. (2012), which covers different w/c ratio, ages and so on. Then using Eq. (6) can be used to calculate the total stress of the second stage. The calculated results are shown in Table. 1.

If approximately estimating the elastic modulus using the following equation (Kosaka et al. 1975):

$$E_m = 1000\{7.7\ln(f'_{cm}) - 5.5\} \tag{7}$$

The strain can be calculated by the simple strain-stress equation:

$$\sigma = E_m \cdot \varepsilon \tag{8}$$

The calculated strain is shown in Table. 2. And also compared with the experimental results of both water saturated and 99% relative humidity. It can be seen that the calculated results are very close to the experimental observations.

Table.1 Calculated radius, volume and stress

	r_{cl}	r_{cv}	$V(r_{cv})$	$V(r_{cl})$	σ_C	σ_L	σ
w/c=0.3	3.28nm	34nm	0.149	0.064	3.25MPa	-9.45MPa	-6.20MPa
w/c=0.5	3.28nm	52.7nm	0.236	0.077	4.93MPa	-12.84MPa	-7.91MPa
w/c=0.7	3.28nm	78.2nm	0.335	0.088	6.62MPa	-16.21MPa	-9.59MPa

Table.2 Comparison between experimental and calculated results

w/c	f'_{cm} (MPa)	E_m (GPa)	Calculated stain (10^{-6})	100% Sat (Experiment) (10^{-6})	99% RH (Experiment) (10^{-6})
0.5	40.77	23.05	343	400 (↑)	500 (↑)
0.5	26.7	19.79	400	450 (↑)	400 (→)
0.5	37.03	22.31	355	200 (↓)	350 (→)
0.7	18.03	16.77	572	450 (↓)	400 (↓)
0.3	51.94	24.92	249	300 (↑)	250 (→)

5. Conclusions

1) A concept of two-stage model is proposed to explain the strain behavior observed in authors' experiments. The first stage is usually for the moisture redistribution caused by hydraulic pressure. And as a result, the hydraulic pressure will be reduced due to this redistribution.
2) The mathematical model of crystallization pressure and negative water pressure is proposed based on the pore size distribution. Using these equations, the strain in the second stage is calculated. And the comparison with the experimental result is in satisfactory agreement.
3) The hydraulic pressure is difficult to evaluate, some simplification should be made to develop a model of hydraulic pressure in the future study.

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