PROBABLISTIC APPROACH FOR SELECTION OF COMPOSITION OF FREEZE-THAW RESISTANT ORDINARY PORTLAND CEMENT CONCRETE

Warda Ashraf [a], Michal A. Glinicki[b], Jan Olek[c]

[a] Department of Civil and Environmental Engineering, University of Maine, Orono, ME 04469, USA.
[b] Institute of Fundamental Technological Research, Polish Academy of Sciences, 02-106 Warsaw, Poland.
[c] Lyles School of Civil Engineering, Purdue University, West Lafayette, IN 47907, USA.

The total number of words in the abstract, text, and references: *4944*
The number of figures and tables: 11

ABSTRACT

This paper features the development of a probabilistic model linking freeze-thaw (F-T) performance of concrete mixtures to their composition. As part of the process of model development, a sensitivity analysis was performed on several concrete mixture parameters to identify these factors that have strong correlations with the F-T resistance of concrete. This sensitivity analysis was performed on 128 sets of experimental F-T test results collected from the literature. The F-T performance level was defined as a discrete measure of the frost resistance of concrete. Finally, a new model to predict the F-T damage of concrete incorporating the variability of the concrete mix parameters (as selected from sensitivity analysis) was developed. This model was developed using only these data sets which contained the results of the relative dynamic modulus of elasticity (RDME) testing performed according to the ASTM C 666 (AASHTO T 161) specifications. Furthermore, only mixtures containing ordinary portland cement (OPC) as a sole type of the binder (i.e., mixtures that did not contain any supplementary cementitious materials) were considered. Additional experimental test results were utilized to validate the model. The reliability of the model was further demonstrated using several examples of concrete mixtures of various compositions. Furthermore, the effects of the number of F-T cycles, air content, paste content, and w/c ratio on the F-T performance of the concrete mixes were demonstrated using the developed model. Accordingly, this model provides the opportunity to optimize the concrete mix proportion for the required performance level of concrete under F-T exposure condition.

Subject Headings: *Freeze-thaw, durability, concrete, pavement, sensitivity analysis, probabilistic design.*

1. Introduction

Damage to concrete pavements and structures caused by F-T actions is an important durability concern, particularly with regard to the serviceability of transportation infrastructure in cold climate regions. The frost damage of concrete is mostly observed in the forms of cracking and spalling due to the expansion of the cement paste during repeated F-T cycles. The F-T deterioration in concrete can also result from the distress occurring within aggregates, but there are established procedures to eliminate such aggregate sources. The characteristics of the cement paste induced frost damage of concrete with different mix parameters have been investigated by numerous research works. However, most of the research outcome in this field presented a deterministic scenario based on the results of laboratory tests mostly following ASTM C666 [1] (AASHTO T 161 [2]). The stochastic nature of concrete properties has not been adequately addressed as far as its frost resistance is concerned.

Probability-based long-term performance evaluation of concrete is critical as it will allow the incorporation of variables resulting from different sources starting from construction practices to actual loading situations. Several probabilistic design approaches were developed for concrete structures exposed to marine environments using the Fick's second law of chloride ion ingress [3-6]. Probabilistic design of concrete pavement for repair and rehabilitation [7], joint movements [8], and cracking [9] can also be found in literature. Despite of high significance only a few design approaches were developed focusing on the required F-T performance of concrete [10, 11]. Cho [10] presented a model to predict the F-T performance of concrete based on regression analysis by response surface method (RSM) considering w/c ratio, air content, and number of F-T cycles as the primary design parameters. In this model [10], the author first predicted the residual strains of concrete elements resulting from the F-T cycles. These strains were then used to forecast the relative dynamic modulus values of concrete during the F-T exposure condition. However, the model proposed by Cho [10] did not consider any variability of parameters resulting from the stochastic nature of concrete. A stochastic model to predict the F-T deterioration in concrete was presented by Duan et al. [11]. In this approach, the concrete was assumed to be composed of discretized microelements. The performances (i.e., the damage level) of these microelements were then assumed to be independent random variables. The limitation of the model proposed by Duan et. al. [11] arises from the fact that it was developed only for non-air entrained concrete whereas most of the pavement concrete produced in the cold regions is air-entrained. Additionally, the model considered only the effect of different w/c ratio on the F-T performance of concrete but not the effects of cement paste content. Moreover, the proposed model did not consider the probability of obtaining a specific F-T performance level of concrete for a given mixture proportions. A different probabilistic approach to model service life is based on Fagerlund [12] model to define the critical degree of concrete saturation as the onset of internal frost damage . However, even in this approach, no relationship has been established between F-T performance based on ASTM C 666 (AASHTO T161) test results and the actual and critical degree of concrete saturation.

The aim of the present paper is to develop a design approach for predicting the F-T resistance of concrete as defined per ASTM C666 (AASHTO T 161) by incorporating the realistic variability of the parameters influencing its performance under such exposure. In order to do so, first, a sensitivity analysis was performed to identify the parameters influencing the performance of concrete while exposed to F-T environmental condition. Then, the variabilities of these selected parameters were incorporated in the design process by means of the probability distribution functions as obtained from the experimental data sets. In this paper, both the sensitivity analysis and probabilistic design approach was developed for concrete containing only OPC (i.e., no supplementary cementitious materials). Nonetheless, a similar approach can be replicated for binary or ternary concrete mixes if the experimental data sets are available.

2. Probabilistic model derivation

2.1 p-value and t-statistics

While reviewing the published literature on the F-T resistance of concrete, data were collected only from those laboratory experiments which followed the standard ASTM C 666 [1] (AASHTO T 161 [2]) testing protocol. The use of the AASHTO/ASTM standard test procedure ensures similar preconditioning and exposure conditions of concrete samples and thus, these parameters were assumed to be constants in the subsequent model derivation. Parameters that were collected from literature included: relative dynamic modulus of elasticity (RDME), conductivity, compressive strength, w/c ratio, spacing factor of the hardened air void system, air content (for both fresh and hardened concrete), and paste content of the concrete mixtures. The initial statistical model was developed under the assumption that all of the above parameters affect the F-T performance of concrete mixture. Then, considering all of the above parameters as input variables and RDME as an output variable a multiple regression analysis was performed using the “Analysis ToolPak” in MS Excel® to establish the initial model linking the RDME values to the previously described input parameters. The regression was performed using the following general equation:

$$y = a_1x_1 + a_2x_2 + \cdots\cdots\cdots + a_nx_n + C \qquad \text{Equation 1}$$

Here,

y = RDME values, C = constant.

x_1, x_2…..x_n are the input parameters (i.e., conductivity, compressive strength, w/c ratio, spacing factor of the air void system, air content, and paste content of the concrete mixtures). a_1, a_2….. a_n are the corresponding coefficients of the input parameters.

Once the initial analysis was completed, the significance of the input variables was evaluated by testing the null hypothesis (i.e., comparing p-values [13, 14] and t-stat [15] for each of the input parameters). The adopted null hypothesis stated that none of the given input variables associated with the model influenced the output (in other words, the coefficient “a_i” corresponding to any given model variable was assumed to be zero). The null hypothesis testing was performed using t-test at the default significance level of 0.05. A low p- value (corresponding to higher value of the t-stat parameter) indicates strong evidence against the null hypothesis and thus, confirms the significance of the input parameter for calculating the output (i.e., RDME).

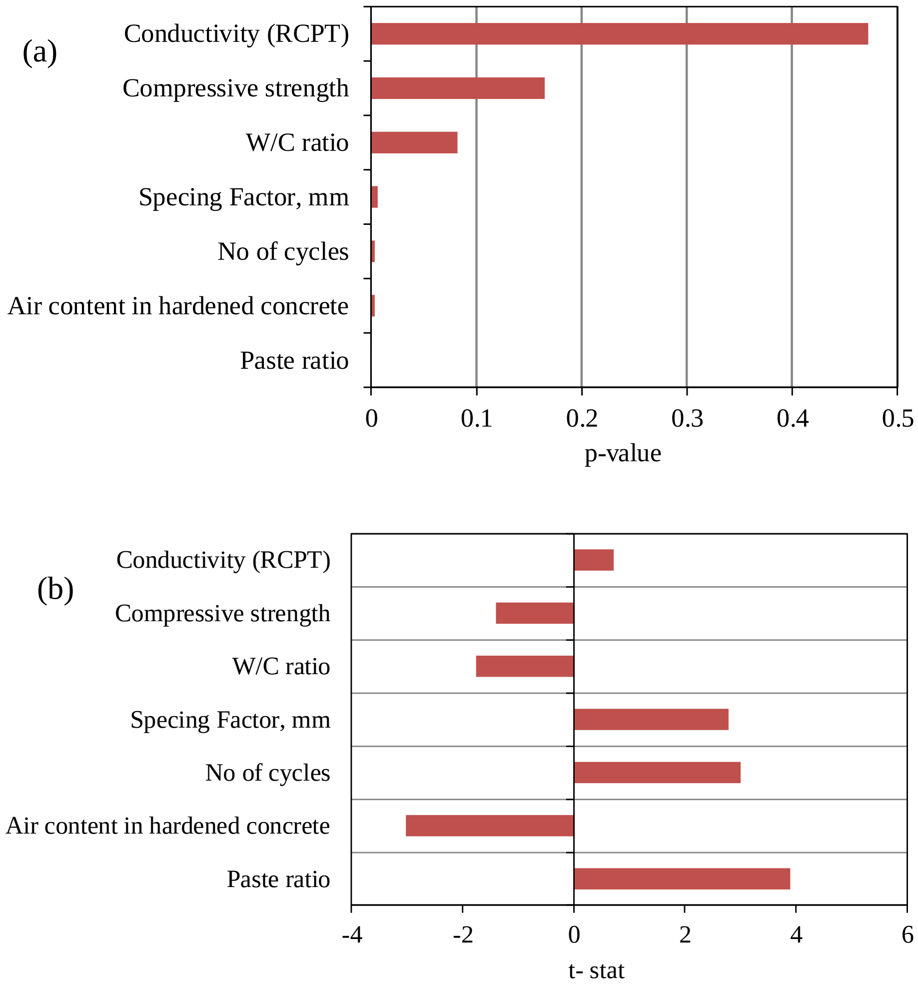


Figure 1: Global sensitivity analysis of the factors affecting freeze thaw resistance of concrete; (a) p-value and (b) t-stat

The regression analysis was performed using around 128 data sets collected from various publications [16-19]. The bar diagrams in Figure 1 (a) and (b) compare the p-values and t-stat, respectively, for the input parameters collected from literature and used in this study. As observed from these Figures, the paste ratio (i.e., paste content of the concrete mixture), air content of hardened concrete, number of F-T cycles, and spacing factors are the four most sensitive parameters having very high t-stat values and low p-values. Another important observation is that the t-stat values of these factors show both positive and negative signs signifying opposite trends of relationship of these parameters with frost resistance of concrete. Moreover, all of these four parameters (i.e., paste ratio, air content of hardened concrete, number of F-T cycles, and spacing factors) are characterized by the p-values below 0.05, which indicates that there is strong presumption against null hypothesis [14]. In case of w/c ratio, the p-value was found to be in between 0.05 and 0.1 indicating that the null hypothesis cannot be rejected. Additionally, this multiple regression analysis indicated that there was no significant relationship of RDME of concrete with its conductivity or compressive strength. Based on these sensitivity analysis results, both, the conductivity and compressive strengths of concrete were eliminated from further considerations during the development of the model linking the composition of the mixture to its expected F-T performance.

2.2 Correlation between hardened and fresh air content

As indicated by the sensitivity analysis (section 2.1), the air content of the hardened concrete is one of the major parameters influencing F-T resistance of concrete. However, it is the air content of the fresh concrete that is usually stipulated in the specifications. In addition, it is also known that there are always discrepancies in the air content of concrete in fresh and hardened states, with the hardened concrete typically containing somewhat less (~ 0.5 to 1%) air. Thus, to account for these discrepancies, the correlation between the air contents of concrete in fresh and hardened states was established.

The correlation between air void parameters of hardened and fresh concrete was derived using the data collected from various research papers [16-19]. When establishing this relationship, it was assumed that the discrepancy between the air content of fresh and hardened concretes is primarily due to mixing, placing, and compaction procedures.

Figure 2 depicts the correlation between the air content of hardened concrete (ASTM C 457 [20]) and fresh concrete as determined by the pressure method (AASHTO T 152 [21]) from 113 concrete mix test results which were collected from literature. This correlation can be expressed by a linear model (Equation 2) for the prediction of air content in hardened concrete from the air content in fresh concrete.

$$A_H = P_1 \times A_F + P_2 \qquad \text{Equation 2}$$

Here, A_H and A_F are air contents of hardened and fresh concrete mixes, respectively. The values of coefficients P_1 and P_2 depend on several factors, including concrete mixing procedure, mix proportions, curing conditions. Realizing the inherent variability of the air void content in both, the hardened and the fresh concretes, when developing the FT model described in section 2.4 of this paper, the values of coefficients P_1 and P_2 were assumed to be normally distributed. As shown in Figure 2, the 95% confidence bands for coefficients P_1 were 0.6179 and 0.8255. Whereas the same bands for coefficient P_2 were 0.5379 and 1.557.

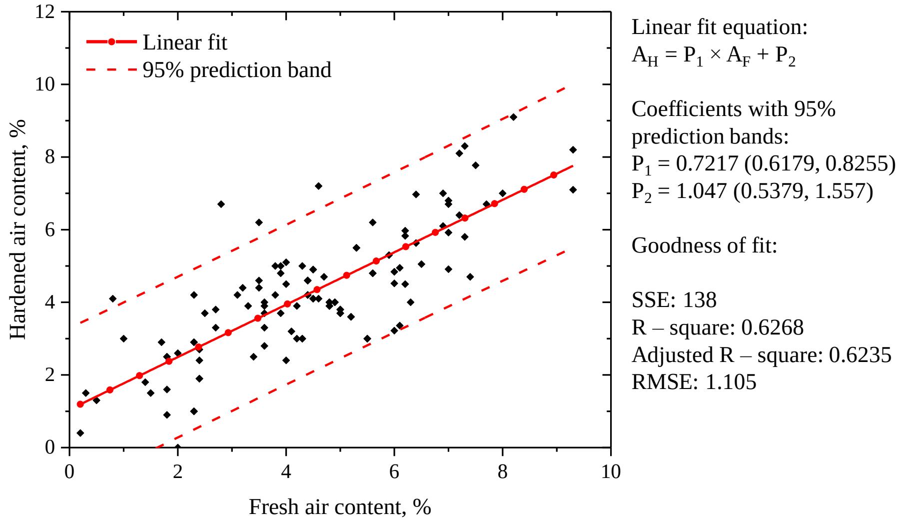


Figure 2: Correlation between air contents of fresh and hardened concrete.

2.3 Correlation between fresh air content and spacing factor

Using the test results from literature, a model for predicting the spacing factor (mm) of the air void system in the hardened concrete from the air content in fresh concrete was generated (Figure 3 and Equation 3).

$$SF = a \cdot \exp(b \cdot A_F) \qquad \mathit{Equation}\ 3$$

Here, SF = spacing factor, mm (as defined in ASTM C 457 [20]).

The coefficients *a* and *b* account for the variability in the spacing factor related to the concrete mixing procedure, mix proportions, type of ingredients etc. Again, similar to the approach utilized when correlating fresh and hardened concrete air contents, the values of coefficient '*a*' and '*b*' were assumed to be normally distributed.

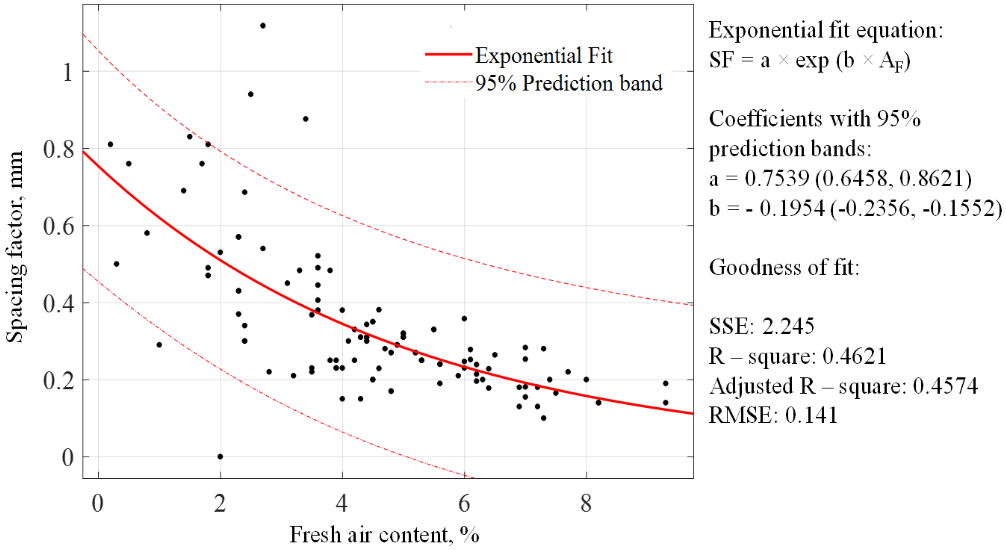


Figure 3: Correlation between spacing factor (mm) and fresh air content of concrete.

2.4 Model for predicting F-T resistance rank

In order to simplify the process of statistical model generation and sensitivity analysis, a new parameter 'freeze-thaw resistance rank (F-T rank)' was introduced. This parameter was based on the RDME values of concrete (as defined in ASTM C 666 [1] and AASHTO T 161 [2]), determined at exposure conditions specified in the standard, and evaluated after any specific number of freeze-thaw cycles. The F-T ranks were assigned for different ranges of RDME values as given in Table 1.

Table 1: Assignments of freeze thaw resistance ranking of concrete based on RDME value.

Freeze Thaw Resistance Ranking	Relative Dynamic Modulus of Elasticity (RDME), %
0	Above 95
1	90 to 95
2	85 to 90
3	80 to 85
4	75 to 80
5	70 to 75
6	65 to 70
7	60 to 65
8	55 to 60
9	Below 55 (considered as failure)

A data set containing 128 experimental test results was gathered from literature to generate the model for the prediction of F-T performance of concrete [16, 19, 22]. Based on nonlinear multivariable regression analysis, the following model (Equation 4) was developed to predict the F-T rank of concrete from given w/c ratio, paste ratio, air content of hardened concrete, spacing factor, and number of F-T cycles.

$$R_{calclated} = k + a_1({}^{W}/_{c})^{b_1} + a_2A_H^{b_2} + \ a_3SF^{b_3} + a_4N^{b_4} + a_5r_p^{b_5} \qquad Equation\ 4$$

Here, $R_{\text{calculated}}$ = Freeze thaw resistance rank.

k, a_1, a_2, a_3, a_4, a_5, b_1, b_2, b_3, b_4, and b_5 are the coefficients.

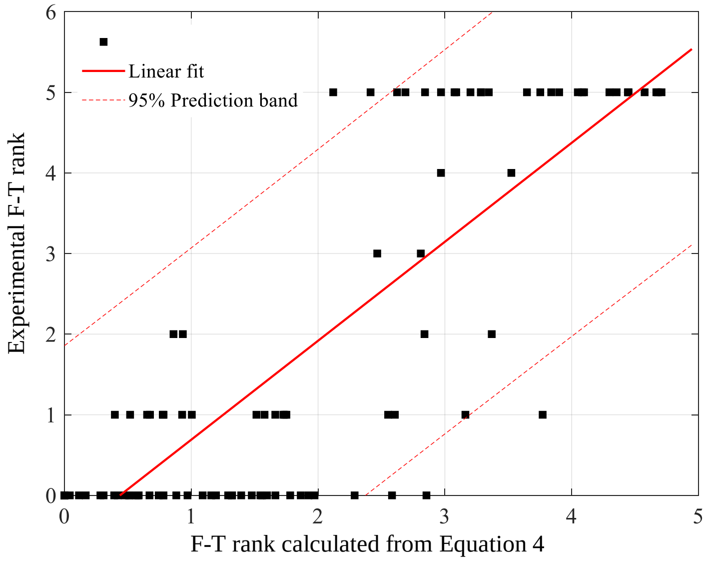
N = No. of F-T cycles.

r_p= paste ratio by mass = (cement + water content)/ (cement + water+ aggregate content).

Using the F-T test results collected from the literature review, the model Equation 4 was further adjusted to determine the error between the F-T rank generated by this equation and the actual F-T rank resulted from experiment (Equation 5 and Figure 4).

$$R_{experimental} = E_F \cdot R_{calculated} + C \qquad Equation\ 5$$

$R_{experimental}$ and $R_{calculated}$ are the F-T ranks determined from experiment and from the model Equation 4, respectively. E_F and C are the coefficients for which the normal distribution of values have been considered.



Linear fit equation:
$R_{\text{Experimental}} = E_F \times R_{\text{Calculated}} + C$

Coefficients with 95% prediction bands:
E_F = 0.9992 (0.8309, 1.167)
C = 0.002962 (-0.3905, 0.3964)

Goodness of fit:

SSE: 189.8
R – square: 0.5837
Adjusted R – square: 0.5795
RMSE: 1.385

Figure 4: Correlation between experimental and calculated F-T ranks from equation 4.

3. Sensitivity analysis of the developed F-T model

At this stage, the sensitivity analysis of the factors affecting the F-T performance of concrete was repeated using the model Equation 4 and following the more accurate (compared to section 2.1) One-Factor-at-a-Time (OAT) method (Morris method, [23]). The model Equation 4 was considered as the objective function for the OAT method [23]. This method, also referred to as the absolute sensitivity analysis, varies a single model parameter while keeping all other parameters constant, and thereby produces a sensitivity ranking based on sum of square errors (SSE). The parameter that produces highest SSE (while being varied) was assumed to be the most sensitive parameter for determining the F-T resistance of concrete. However, it should be noted that the outcome of this sensitivity analysis is dependent upon factors such as selection of objective function, values of fixed parameters, sampling methods.

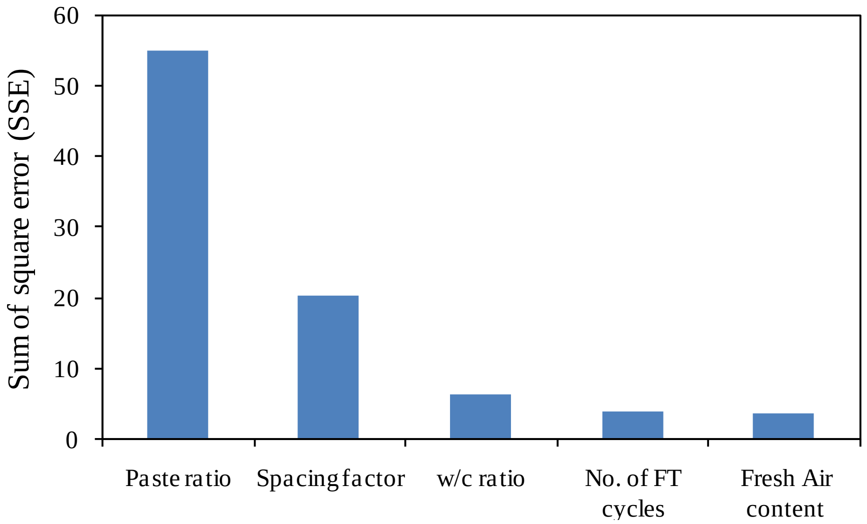


Figure 5: Sensitivity analysis of F-T rank based on OAT method.

Figure 5 shows the sensitivity analysis results for the F-T rank of concrete based on the model Equation 4. From this analysis, paste ratio of concrete mixture and spacing factors of the air void system in the hardened concrete were found to be the most sensitive factors for F-T performance of concrete.

4. Application of the developed model

4.1 Description of use

To determine the hardened air content from fresh air content the procedure known as probability sampling was used. Using this procedure, for each trial run the model will randomly select a pair of P_1 and P_2 factors (assuming that these factors were normally distributed) and insert those into the model Equation 2 to calculate the value. Thus, after sufficient number of trials, the probability distribution of the air content of hardened concrete can be determined. Using similar process, the probability distribution of spacing factor of air void system for any particular fresh air content of concrete can also be found using Equation 2. Once the distribution of hardened air content (A_F) and spacing factor (SF) are known, the probability distribution of F-T rank can be determined from Equation 4 and Equation 5 for any specific concrete mix proportions (i.e., w/c ratio and paste ratios) after specific number of F-T cycles. Higher number of trials will result in more accurate distributions and will also increase the calculation time. Thus, the selection of trial numbers depends on user’s requirements and preferences. In all calculations and results given in this paper, the number of trials was 1000. The following sections describe the validation process and an illustrative example of the usage of the developed probabilistic model for predicting F-T performance of concrete.

4.2 Validation of the model

To validate the model, a separate data set, containing 27 experimental results, was collected from literature [24]. The test results were collected only from those experiments which followed

ASTM C 666 [1] (AASHTO T 161 [2]) and used OPC concrete without any supplementary cementitious materials. The correlation between the predicted F-T rank from the model and the experimental F-T rank is given in Figure 6. The coefficient of determination (R^2) value between the predicted and experimental F-T rank found to be 0.6905, which indicates good reliability of the developed model.

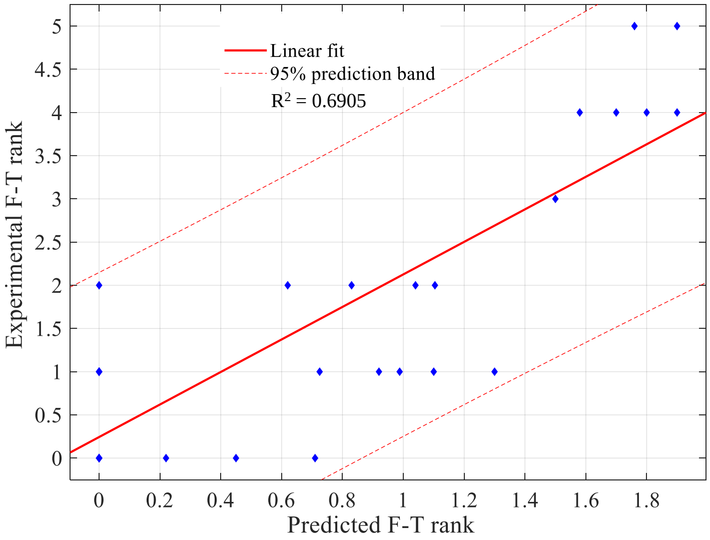


Figure 6: Correlation between experimental and predicted F-T rank.

4.3 Example of the application of the model

This section illustrates the application of the proposed probabilistic model to predict the F-T performance of two different concrete mixtures. The characteristics of these mixtures are as follows: mix-1: w/c ratio = 0.42, paste ratio = 0.22, air content = 3% and mix-2: w/c ratio = 0.55, paste ratio = 0.22, air content = 2%. When performing the analysis, the maximum F-T rank of 4 (minimum RDME value 75) after 300 F-T cycles was selected as desirable performance level. Figure 7 presents the relative probability distribution plots for air content and spacing factor in hardened concrete for both of these mixtures. From these Figures, it can be observed that the probability density function for hardened air content are normally distributed whereas for spacing factor the probability density function is lognormal. These distributions of air content and spacing factor are then incorporated in Equation 4 and Equation 5 to determine the probability distribution of F-T rank after a specific number of F-T cycles. The relative probability and cumulative probability distributions of the F-T ranks for mix-1 and mix-2 after 300 F-T cycles (as per ASTM C 666 [1]) are given in Figure 8. Figure 8 (b) suggests that there is around 76% probability that the resulted F-T rank for mix-1 will be lower than 4 after 300 F-T cycles and hence, 76% probability that this mixture design will satisfy the design requirements. However, in case of mix-2 (Figure 8 (d) the probability of satisfying the design criteria is only around 6%.

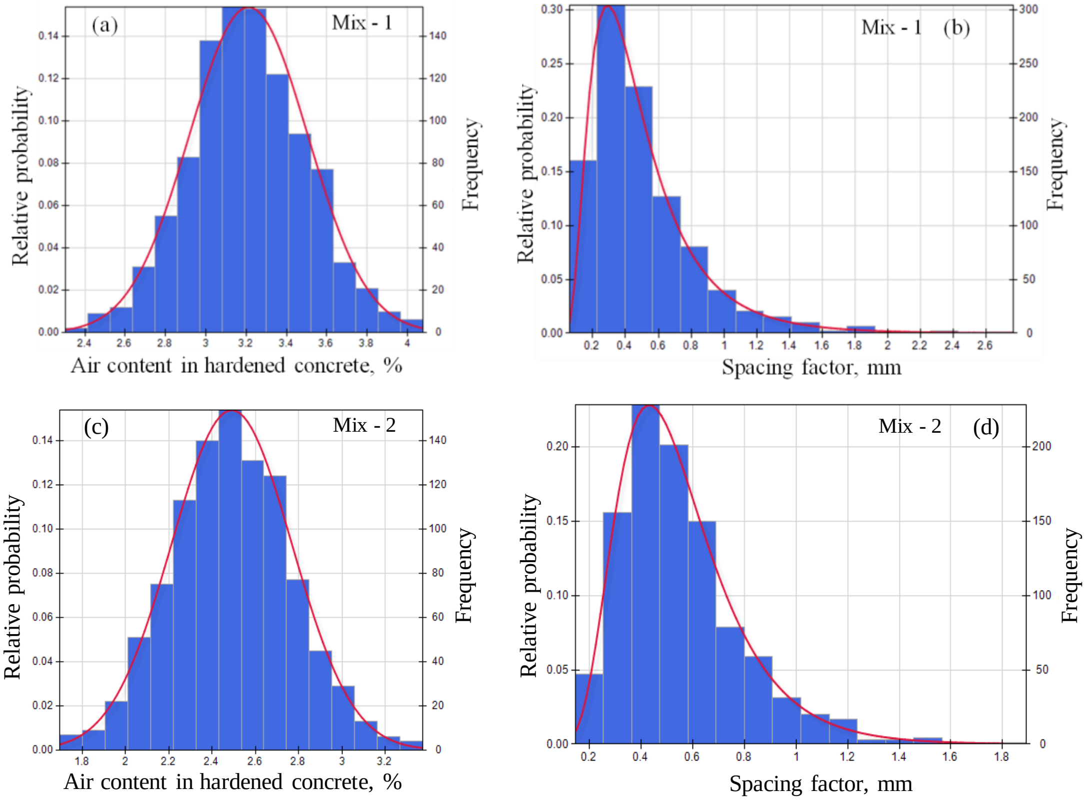


Figure 7: Relative probability distribution of (a) air content in hardened concrete for mix-1, (b) spacing factor for mix -1, (c) air content in hardened concrete for mix-2, and (d) spacing factor for mix -2.

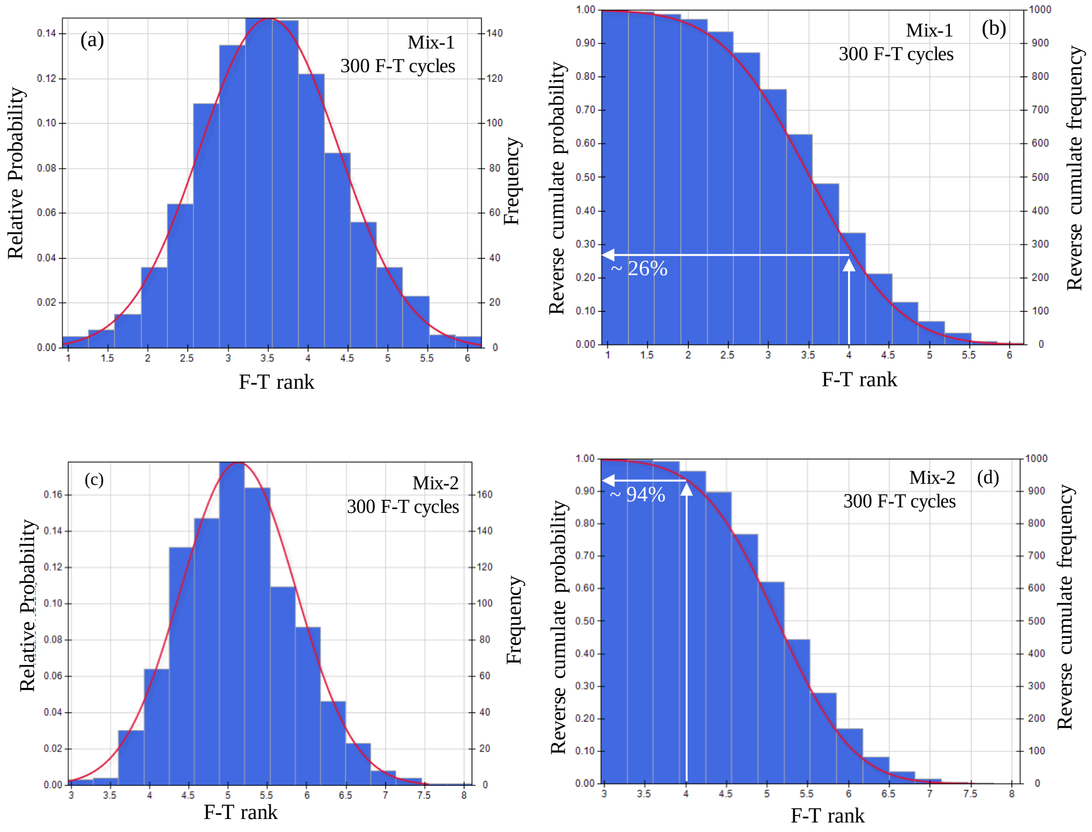


Figure 8: (a) Relative probability distribution of predicted F-T rank for mix-1, (b) cumulative probability distribution of predicted F-T rank for mix-1, (c) Relative probability distribution of predicted F-T rank for mix-2, and (d) cumulative probability distribution of predicted F-T rank for mix-2 after 300 F-T cycles.

4.4 Effects of F-T cycles, air content, w/c ratio, and paste ratio

Previous section explained the steps that need to be followed to obtain the distributions of F-T rank for a particular mix proportion after a specific number of F-T cycles. Similar steps can be repeated to obtain the variations of distress levels (in terms of F-T rank) with number of F-T cycles for any particular concrete mix proportion. As an example, Figure 9 (a) shows the variation of F-T rank with F-T cycles for mix-1. From this Figure, it can be projected that the lowest F-T rank (i.e., F-T rank of 5 or RDME 65 to 70%) this mixture will achieve after 400 F-T cycles. To facilitate the readers to justify the rationality of the model output, similar illustrations for some conventional concrete mixes are given in Figure 9 (a ~ f). These illustrations can also be used to predict the probable timeline to initiate the distresses in concrete for given concrete mixture proportions, information which can be further used to correlate with service life performance.

Using a similar process, the effects of air content, w/c ratio, and paste ratio on the F-T performance of a particular concrete mix are determined and presented in Figure 10 (a), (b) and (c), respectively. From Figure 10 (a) it can be observed that the confidence bounds for predicted F-T rank expanded with higher air contents of fresh concrete. This observation is justified from the practical point of view that variability of hardened air content due to the concrete mixing procedure is expected to increase in case of higher fresh air content. F-T performance of concrete was found to be reduced with an increase in the w/c ratio as shown in Figure 10 (b). This finding matches with model generated by Cho [10], which also predicted poorer F-T resistance of concrete with higher w/c ratio. From Figure 10 (c), the performance of concrete under F-T exposure conditions can be expected to be improved with higher paste content of the concrete mixture. However, it was not possible to validate or compare this finding with any other results since no other previous research works (both experimental and model based) investigated the effect of paste content on the F-T performance of concrete. Nonetheless, it is worth noting that such approach for evaluating the effects of individual mix parameters on the F-T performance of concrete can be utilized for optimizing the concrete mixture proportions.

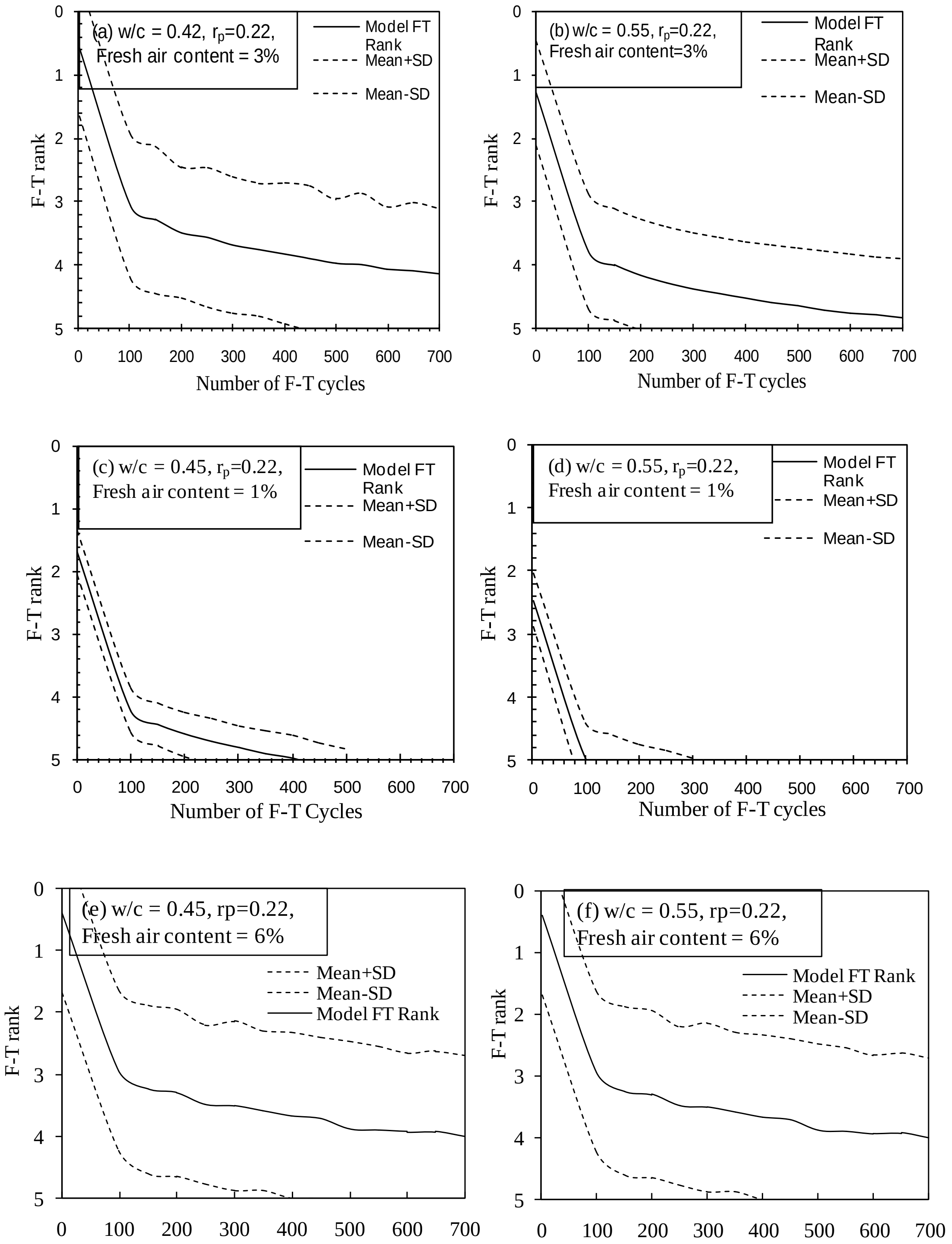


Figure 9: Variation of predicted F-T rank with number of F-T cycles for various concrete mixes, (a) w/c = 0.42, r_p=0.22, fresh air content = 3%, (b) w/c = 0.55, r_p =0.22, fresh air content = 3%, (c) w/c = 0.45, r_p =0.22, fresh air content = 1%, (d) w/c = 0.55, r_p =0.22, fresh air content = 1%, (e) w/c = 0.45, r_p =0.22, fresh air content = 6% and (f) w/c = 0.55, r_p =0.22, Fresh air content = 6%

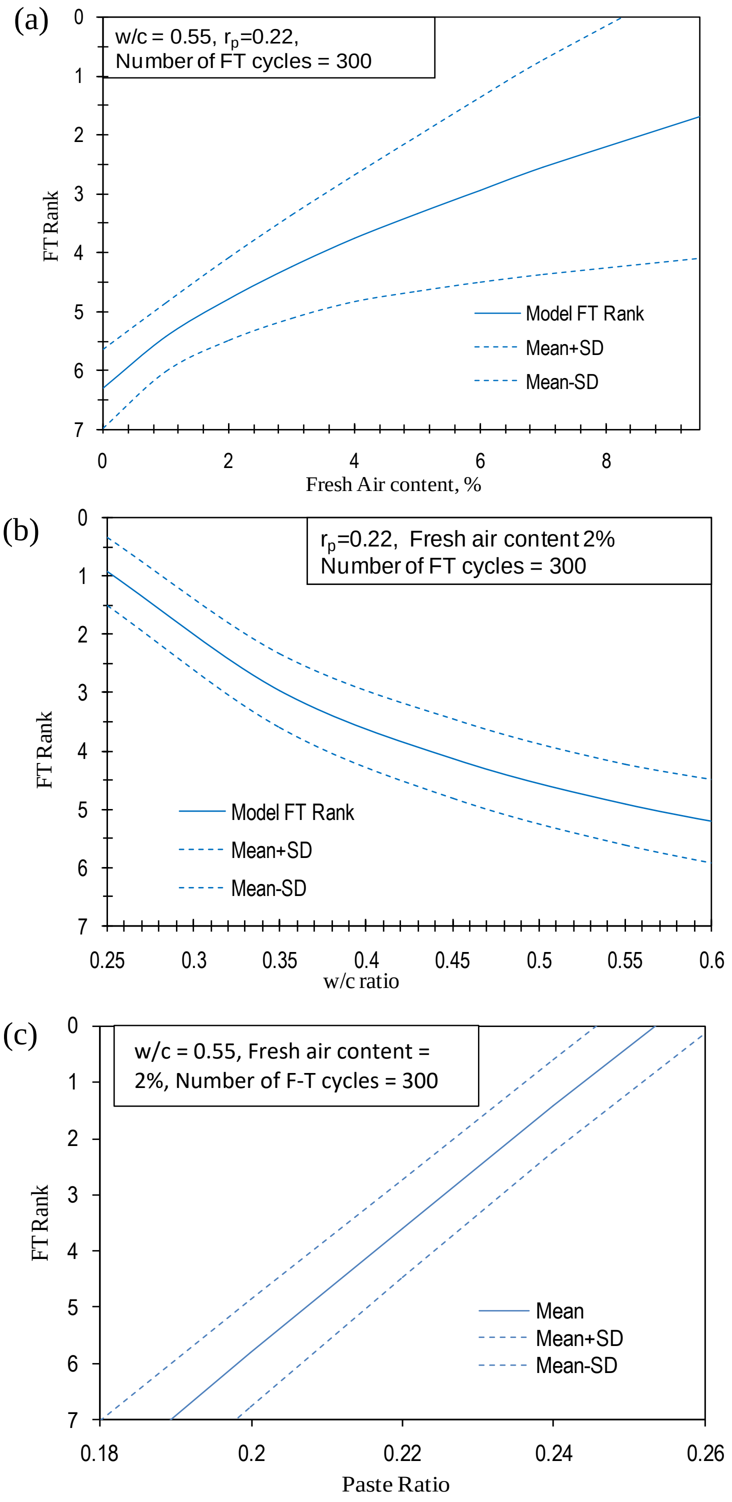


Figure 10: Effects of (a) fresh air content, (b) w/c ratio and (c) paste ratio on predicted F-T performance of concrete.

The proposed model/methodology can be further used to predict the service life performance of concrete. It can also be used to identify optimum concrete mix parameters (i.e., w/c ratios, paste ratios, and fresh air content) to obtain target performance under F-T conditions. The limitation of the model arises from the fact that this particular model is valid only for concrete mixes containing OPC (no supplementary cementitious materials) and also, it predicts the F-T performance based only on ASTM C 666 [1] (AASHTO T 161 [2]) test results. It should be noted that the main objective of this paper was to develop an innovative approach to incorporate the variability of the parameters to determine the probability distribution of F-T distress in concrete. Given the required experimental data set, same approach can be modified for concrete mixes containing supplementary cementitious materials or tested in accordance to any other standard test procedure.

CONCLUSIONS

The sensitivity analysis of the existing experimental data set identified that the paste ratio of the concrete mixture and the spacing factor of the entrained air void system are the most significant parameters affecting the performance of concrete under F-T cycles. This sensitivity analysis also allowed for the formulation of a new approach for probabilistic evaluation of the F-T performance of concrete. In the proposed approach, the relative dynamic modulus of elasticity (RDME) value as per ASTM C 666 (AASHTO T 161) was used to define the 'F-T resistance ranks'. The stochastic nature of concrete properties was characterized by the probability distribution of the parameters that characterize the relationship between the air content in hardened concrete and in fresh concrete, and also, the relationship between the spacing factor of air voids in hardened concrete and the air content of fresh concrete. Other stochastic effects were incorporated in the development of the model. These included considerations of a random distribution of parameters that characterize the correlation between the F-T resistance of both, the experimental data and calculated values. The developed model revealed the following characteristic features of the F-T performance of concrete:

- The variability of F-T performance of concrete was found to increase with an increase in the air content. At the same time, as expected, the F-T performance was also observed to improve with the increase in air content.
- The developed model enables users to investigate the effects of w/c ratio and paste content on the F-T performance of concrete. The higher w/c ratio was found to degrade the F-T resistance of concretes. On the other hand, the higher paste content was found to improve the F-T performance of concrete.

With respect to the limitation of the model, it should be noted that it was developed only for concrete containing OPC (i.e., concrete without any supplementary cementitious materials for paste content from 0.19 to 0.27 and w/c ratio 0.25 to 0.55). However, given the required experimental data set, the presented probabilistic design approach can be replicated for other types of concrete mixtures.

REFERENCE

[1] ASTM C 666. Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing. *ASTM International*, 2008.

[2] AASHTO T 161. Standard Method of Test for Resistance of Concrete to Rapid Freezing and Thawing. *AASHTO*, 2017.

[3] Duan, A., J.G. Dai, and W.L. Jin. A probabilistic approach for durability design of concrete structures in marine environments. *Journal of Materials in Civil Engineering*,

Vol. 27, No. 2, Special issue: Sustainable Materials and Structures, 2014.

[4] Sengul, O. Probabilistic design for the durability of reinforced concrete structural elements exposed to chloride. *Digest*, Vol. 22, No. 2, 2011, pp. 1461 – 1475.

[5] Deby, F., M. Carcassès, and A. Sellier. Probabilistic approach for durability design of reinforced concrete in marine environment. *Cement and Concrete Research*, Vol. 39, No. 5, 2009, pp. 466–471.

[6] Arteaga, E. B., A. Chateauneuf, M. S. Silva, P. Bressolette, and F. Schoefs. A comprehensive probabilistic model of chloride ingress in unsaturated concrete. *Engineering Structures*, Vol. 33, No. 3, 2011, pp. 720–730.

[7] Lepech, M. D., M. Geiker, and H. Stang. Probabilistic design and management of environmentally sustainable repair and rehabilitation of reinforced concrete structures. *Cement and Concrete Composites*, Vol. 47, 2014, pp. 19–31.

[8] Lee, S. A probabilistic model for joint-movements in jointed concrete pavement. *KSCE Journal of Civil Engineering*, Vol. 7, No. 2, 2003, pp. 141–146.

[9] Tailhan, J. L., S. Dal Pont, and P. Rossi. From local to global probabilistic modeling of concrete cracking. *Annals of Solid and Structural Mechanics*, Vol. 1, No. 2, 2010, pp. 103–115.

[10] Cho, T. Prediction of cyclic freeze–thaw damage in concrete structures based on response surface method. *Construction and Building Materials*, Vol. 21, No. 12, 2007, pp. 2031–2040.

[11] Duan, A., Y. Tian, J. G. Dai, and W. L. Jin. A stochastic damage model for evaluating the internal deterioration of concrete due to freeze–thaw action. *Materials and Structures*, Vol. 47, No. 6, 2014, pp. 1025–1039.

[12] Fagerlund, G. *A service life model for internal frost damage in concrete*. Report TVBM; Vol. 3119. Division of Building Materials, LTH, Lund University, 2004.

[13] Wikipedia. *p-value, The Free Encyclopedia*. http://en.wikipedia.org/wiki/P-value. Accessed January 15, 2017.

[14] Rumsey, D. J. *What a p-value tells you about statistical data*. http://www.dummies.com/how-to/content/what-a-pvalue-tells-you-about-statistical-data.html. Accessed January 15, 2017.

[15] Wikipedia. *t-statistic, The Free Encyclopedia*, http://en.wikipedia.org/wiki/T-statistic. Accessed January 15, 2017.

[16] Wang, K., G. Lomboy, and R. Steffes. *Investigation into freezing-thawing durability of low-permeability concrete with and without air entraining agent*. Report: National Concrete Pavement Technology Center, 2009.

[17] Ronning, T. F. *Freeze-thaw resistance of concrete effect of : curing conditions , moisture exchange and materials*. The Norwegian Institute of Technology, Thesis, 2001. http://www.divaportal.org/smash/get/diva2:126219/FULLTEXT01.pdf . Accessed January 15, 2017.

[18] Cramer, S. M. and J. R. A. Walls. *Strategies for enhancing the freeze-thaw durability of portland cement concrete pavements*. Publication Grant no. WisDOT SPR # 0092-45-76. Wisconsin Department of Transportation, 2001.

[19] Tanesi, J. and R. Meininger. *Freeze-thaw resistance of concrete with marginal air content*. Publication HRT-06-117. Federal Highway Administration (FHWA), 2006.

[20] ASTM C 457. Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete. *ASTM international*, 2012.

[21] AASHTO T 152. Air Content of Freshly Mixed Concrete by the Pressure Method. *AASHTO*, 2017.

[22] Lomboy, G. and K. Wang. Effects of strength, permeability, and air void parameters on freezing-thawing resistance of concrete with and without air entrainment,” *Journal of ASTM International*, Vol. 6, No. 10, 2009, pp. 1-14.

[23] Morris, M. Factorial sampling plans for preliminary computational experiments. *Technometrics*. Vol. 33, No. 2, 1991, pp. 161–174.

[24] Masad, E. and L. James. Implementation of high performance concrete in Washington state. Publication WA-RD 530.1. Washington State Department of Transportation, 2001.