PREDICTION OF FREEZE–THAW RESISTANCE OF GGBFS CONCRETE BASED ON ANN MODELS

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Received: 15.10.2014; Revised: 20.12.2014; Accepted: 15.01.2015

Abstract

In the paper the neural network modelling approach was used to construct an ANNs model to investigate the influence of mix proportion on freeze–thaw GGBFS concrete internal cracking resistance. The simplest way to prevent the internal cracking due to freeze–thaw cycles is the good air-entrainment with an adequate air void spacing. The first step in developing the network was collecting the data set containing the information about mix proportion parameters, characteristics of physical structure of hardened concrete (absorption, permeability, compressive strength) and freeze–thaw durability test results obtained in laboratory using the method of polish standard PN-B-06250:1988. The collected data dealt with normal and high strength concretes made with cements: CEM I, CEM II/A,B-S and CEM III/A, air-entrained or not. The four classes of freeze–thaw durability were used in assessing the concrete resistance to internal cracking.

Streszczenie

W referacie przedstawiono rezultaty wybranych analiz wykonanych przy użyciu sztucznych sieci neuronowych aby zbadać wpływ składu betonu na jego mrozoodporność. Najprostszym sposobem zapewnienia mrozoodporności jest właściwe napowietrzenie z odpowiednim rozstawem porów powietrznych. Pierwszym etapem tworzenia sieci było zebranie informacji zawierających informację o składzie mieszanki betonowej, właściwościach fizycznych i strukturze wewnętrznej badanych betonów (absorpcja kapilarna, przepuszczalność, wytrzymałość na ściskanie) oraz przeprowadzenie testów mrozoodporności zgodnie z PN-B-06250:1988. Zebrane dane dotyczyły betonów wykonanych na cementach CEM I, CEM II/A,B-S i CEM III/A, napowietrzonych lub nienapowietrzonych. W zależności od straty wytrzymałości próbek zamrażanych metodą zwykłą PN po 150 cyklach zamrażania-rozmrażania wprowadzono pojęcie 4 klas mrozoodporności.

Keywords: **Air entrainment; ANN Model; Durability; Frost resistance; GGBFS concrete.**

1. INTRODUCTION

The proper design (the selection of ingredients and proportions) and the diagnosis of slag cement concretes involves the knowledge of the mutual relations between the composition, the physical properties and the frost resistance, requires establishing the guidelines in this respect. The practical aspect of the concept proclaiming that the concretes including additives are of equal efficiency is not very clearly explained, and neither are the methods of its verification, e.g. by testing the frost-resistance. HPC is less sensitive to freezing and thawing action than normal concrete because HPC usually develops more self-desiccation and has a lower and finer capillary porosity [2].

A significant portion of the concrete in the maintained structure [4] is only partially saturated with water, and the rate of the water and dissolved salts absorption depends on the capillary phenomena. It is therefore believed that the absorbability and capillary absorption increase are important factors that permit the quantitative assessment of the durability of porous cement materials. Nowadays, there are various laboratory tests in use (according to European and

American standards) examining concrete frost resistance. However, they are not clearly related to the XF exposure classes, taking into account the degree of water saturation and the use of de-icing salts. The information about the initial state of the concrete saturation with water is not sufficient to predict how it will behave during the repeated freeze–thaw cycles. The absorption of external water is a key parameter in controlling the mechanisms of internal damage caused by freezing-thawing cycles [2]. In the PN method the forced air circulation in the freezing chamber can cause the surface desiccation of the specimens and then the performance of even a few hundred cycles will not lead to the concrete destruction. The same concrete frozen in water may behave quite differently. Simple and quick indirect tests to assess the frost-resistance on the basis of other characteristics of fresh or hardened concrete have been worked on for a long time. They include tests based on measuring one feature or a combination of qualities: the air content, the pore size distribution, the absorbability, the degree of saturation, the capillary absorption and the compressive or tensile strength.

Certain researchers [5] opted for the complete abandonment of the absorbability criterion, while others advocated the development of more precise methodology and the change of the criterion. The individual experience [6], shows that the air pore structure determines concrete frost resistance in the case of air-entrained concretes. Other parameters of air-entrained concrete, including strength and absorbability, are of secondary importance. However, as far as non-air-entrained concretes are concerned, this may not be the case.

A question can be asked whether a relatively simple rapid chloride permeability test [7] could be used in concrete quality evaluation instead of the absorbability criterion.

The paper presents the outcome of the selected analyses investigating the results of the several concrete series tests. The results were obtained from testing concretes made with a binder containing different contents of blast furnace slag in the range of 0-55% and the aggregate of igneous rocks. Depending on the strength loss of the specimens frozen according to the ordinary PN method, 4 classes of frost-resistance were distinguished after 150 freeze–thaw cycles.

2. THE TEST RESULTS ANALYSIS

The analysis focused on the results of tests conducted on several concrete series with very diverse compositions and properties. The concretes included different binders: the cements such as CEM I, CEM II/A/BS, CEM III A or CEM I + the addition of slag, crushed coarse aggregate (D = 16 mm) air entrained

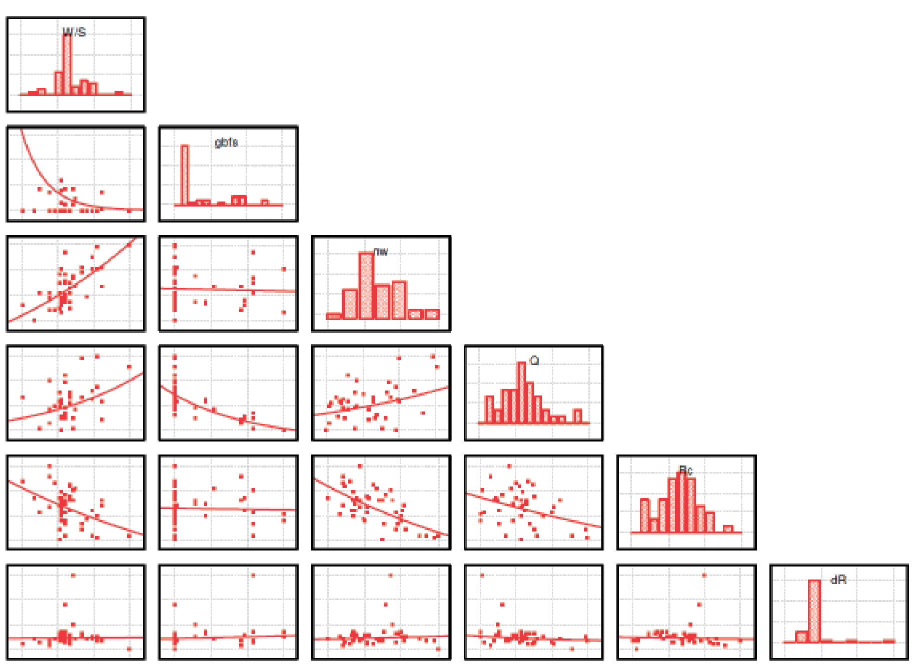

Figure 1.
Relations between examined factors for air-entrained concretes

and not air entrained.

The following features were taken into account, serving as the assumed factors:

- water-binder ratio *W/B*,
- the slag content in the binder s%,
- compressive resistance R_c on the 10 cm cubes, MPa,
- absorbability a_w, %,
- chloride permeability determined by the RCPT method [7] *Q*, coulombs,
- and the resulting factor – a relative decrease in concrete strength *dR* after 150 freeze–thaw cycles using an ordinary PN-B-06250:1988 [11] method.

The general characteristics of the various investigated factors and the relationships between them are shown in Figures 1 and 2, separately for air-entrained and non-air-entrained concrete. As can be concluded from Fig.1, the frost-resistance (*dR*) of air-entrained concretes depends on the quality of air-entrainment, with other dependencies being of little significance here. This confirms the appropriateness of the PN-EN 206-1 standard recommendations, according to which the air-entrainment with the air content of above 4% should provide the concrete frost resistance – the research should focus on evaluating the quality of the air pore structure according to the PN-EN 480-11. Therefore the further research will cover only those concretes in which air-entrainment was not applied.

In the case of the non-air-entrained concretes (Fig. 2), the fairly close, nonlinear relations between the analysed factors can be observed. Both the factors associated with the paste composition (*W/B*, *s%*) and those which determine the porosity and permeability of concrete (a_w, *Q*, R_c) have an effect on frost-resistance. These are the factors characterizing the "bulk" properties of concrete, which are responsible for the resistance to internal cracking of concrete. The paste composition alone (*W/B* and *s%*) is not enough to describe the properties of the porous structure of concrete – the additional information describing the concrete structure is necessary. The additional information can provide the data on the strength, absorbability and permeability.

It is not, however, insignificant whether the “ready” slag cement is applied or whether the ground slag is added to Portland cement. Slag cement, produced in a cement plant, is typically characterized by uniform grinding, thanks to which the concrete achieves more favourable parameters. Therefore, in order to better define the properties of the concrete structure, an additional factor *R_B* designating the type of the applied binder was introduced. It can take the following values: 0 – cement CEM I, 1 – slag cement, 2 – Portland cement CEM I + the slag addition.

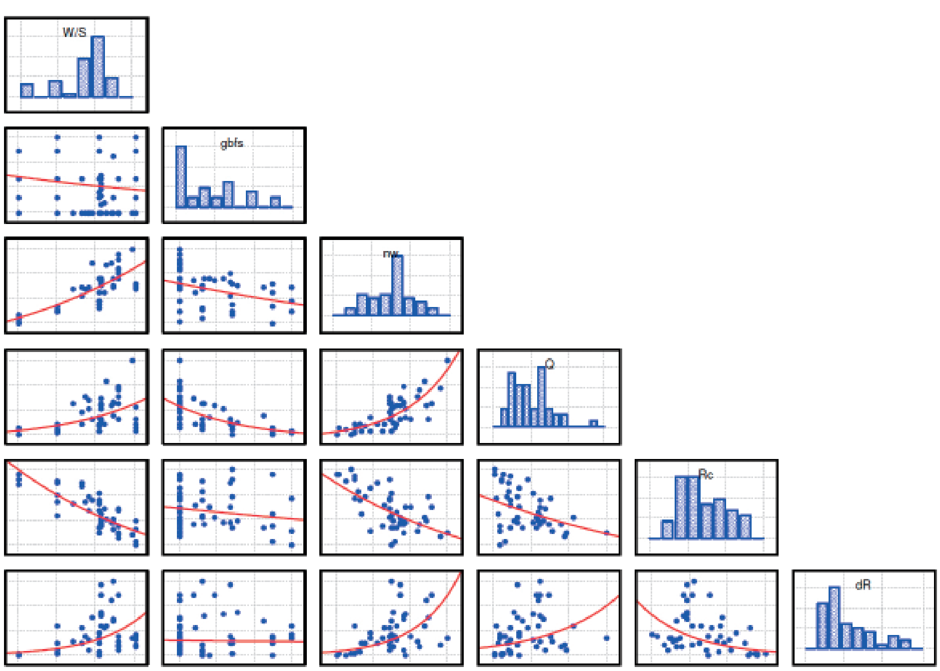

Figure 2.
Relations between examined factors for non air-entrained concretes

There was an attempt to link the results of the determined concrete frost-resistance, obtained by using an ordinary method, to its composition and to the results of investigating the physical characteristics of air-entrained concrete through defining the relations of the *dR* = *f*(X1,X2,…, Xn) type, using the technique of the artificial neural networks analysis. The analysis of artificial neural networks (ANN) is a significantly simpler and faster method than the traditional statistical analysis methods, especially in the case of modelling nonlinear multifactorial dependencies. Artificial neural networks have frequently been used to describe the mutual dependencies and for predicting various properties of concrete. During investigations the Q_net'97 program has been used [12].

The diagram of an exemplary three layered artificial neural network having the structure [3-4-1] has been used, i.e. three input nodes, four nodes in the hidden layer one output node.

A number of trials were performed while determining a relation *dR* = *f*(X1,X2,…, Xn) between the combinations of the analysed factors, and assuming different models of the ANN lattice.

Eventually the model with a 3-layer lattice with the [5-6-1] structure was adopted. The model analyses the effect of 5 factors on frost-resistance: *R_B, W/B, s%*, R_c, *Q*. The learning process provided the results, which were presented in Table 1 (not applied in the calculations due to an inadequate number of the learning patterns).

Table 1.
The learning process

Learning patterns number	RMS error	Correlation coefficient
43	0.0385	0.975

The crucial aspect of the presented approach is an attempt to develop a tool for assessing the degree of frost-resistance on the basis of the knowledge of the composition and basic physical properties of concrete. The factors included in the ANN-*dR* model can be determined after 28 days of curing and are known prior to the assessment of the potential degree of concrete frost resistance. If the assessment of frost resistance is regarded positive, the further extensive studies of frost-resistance by repeated freeze–thaw cycles can be abandoned.

Examining the relations between the particular factors by analysing the ANN lattice as a function of five variables poses a number of problems. The values of

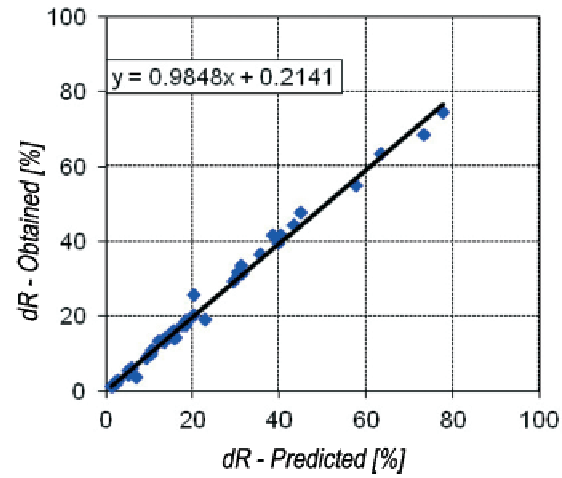

Figure 3.
Correspondence between observed results and ANN-*dR* lattice-derived results

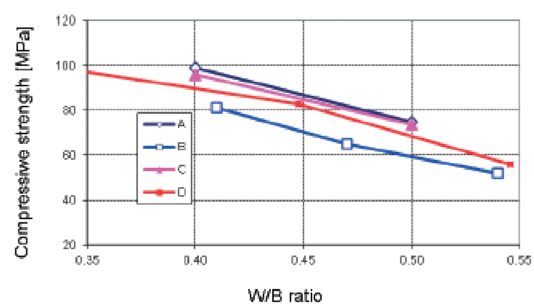

Figure 4.
The dependency of the R_c strength on the *W/B* ratio for concretes with the following bindings: A-B series – the CEM I cement; C – a binder comprising 34% of the slag addition in the dry weight, D – the CEM II/B-S cement

the variables need to be adopted within the area included in the field of the experiment. The adoption of values from outside the measurement range can lead to erroneous estimates. Only the *W/B* ratio, the *R_B* type of the applied binder and the *s%* content of the slag are independent variables, whereas other variables: aw, absorbability, Q permeability and Rc resistance are response variables, dependant on the listed factors related to the composition of the cement paste. It is not easy to establish simple dependencies, such as $Q = f(W/B, s\%, R\_B)$ and $R_c = f(W/B, s\%, R\_B)$, as these relations are of complex character.

The examples of defining the effect of the *W/B* ratio, the type of binder, the strength and the permeability on the degree of frost resistance, expressed as a *dR* decrease in the resistance, are presented below. The Figures 4-6 show the role of the binder (2 different

CEM I Portland cements of the A and B series, slag cement – C series; CEM I cement + addition of slag – D series) in the development of strength, permeability and frost resistance of concrete.

Both cements with slag, characterized with a lower permeability and high strength, have a better frost resistance than concretes made with the use of Portland cement.

The concrete – "A" has a higher strength and lower permeability than "B", which makes it more frost-resistant. In the case of cements containing slag, the higher strength and permeability of concrete "C" is associated with lower frost resistance in relation to the slag concrete "D".

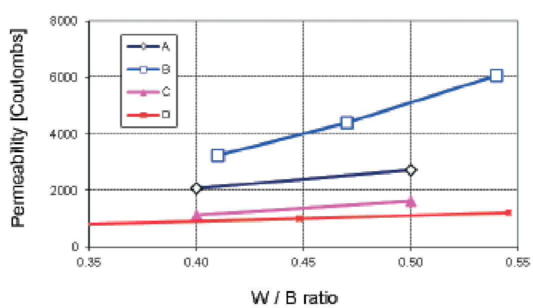

Figure 5.
Relation between the *Q* permeability and the *W/B* ratio for concretes with the bindings: A-B series – CEM I cement; C series – the binding containing 34% of slag in the dry weight, D series – CEM II/B-S series

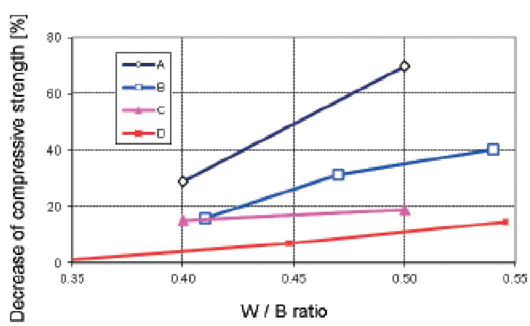

Figure 6.
Decrease in strength calculated using the ANN-*dR* lattice for the W/B ratio of the A-D series concretes assuming the parameters Rc and Q, as shown in Figures 5 and 6

In the authors' opinion the binary assessment of frost-resistance (frost-resistant vs. non frost-resistant) is not a good solution (at dR = 19.5 concrete being non frost-resistant, whereas at 20.5 being frost-resistant). It would be better to introduce a 4-grade rating scale (4 classes of frost-resistance:1-very good, 2-good, 3-inadequate, 4-very weak) assuming the dR boundary values: 10%, 20%, 40%.

3. CONCLUSIONS

The paper analyses the relations between the composition, physical properties and the results of concrete frost-resistance tests conducted with an ordinary method PN-B-06250:1988. The analysis covered over 90 series of air-entrained and non-air-entrained concretes manufactured with bindings containing a varied slag content (the slag cements: CEM II/A,B-S, CEM III/A, cement CEM I or CEM I + the addition of slag).

The analysis attempted to develop a dependency model enabling forecasting the level of concrete frost-resistance on the basis of the knowledge of the paste composition (the kind of binding, the W/B ratio and the slag content in the binding) as well as the parameters defining the quality of the hardened concrete (a_w, absorbability, RCPT permeability and R_c strength). Moreover, the possibility of replacing the water absorbability with the RCPT permeability as an alternative parameter used to assess the quality of concrete was under consideration.

After the initial analysis it was found that in the case of the air-entrained concretes the frost resistance is determined by the quality of air-entrainment, with the dependencies between the composition and the physical properties of the hardened concrete being of secondary importance. The control tests should focus on assessing the quality of air entrainment in accordance with the PN-EN 480-11 standard.

In the case of non-air-entrained concretes (43 series of concretes) one can distinguish two main groups: the HPC airtight structure concretes and more porous concretes with medium strengths. The HPC high strength concretes ($R_c > 70$ MPa, the $W/B \leq 0.35$) have a good frost resistance regardless of the type of the applied binder.

It has been found that in the group of normal strength concretes there are non-linear relations between the above-mentioned physical factors. These relationships are complex in nature and, therefore, in order to develop mathematical dependencies, it was decided to apply the method of the artificial neural networks analysis. Eventually, a variant of a 3-layer artificial neural network ANN-$dR = f\{R\_B, W/B, s\%, R, Q\}$ of the [5-6-1] structure, was developed. It permits a good prediction of the dR concrete strength decline after 150 freeze–thaw cycles. By introducing a 4-grade scale to assess the degree of frost resistance (4 classes of frost resistance) it is possible to correctly classify the concrete of a known composition, permeability and durability (the absorbability can be omitted in the text).

The factors included in the ANN-*dR* model can be determined after 28 days of curing and provide a basis for assessing the potential degree of the concrete frost resistance. If the results of this evaluation are considered positive, it will be possible to abandon further excessive studies of frost resistance by means of the freeze–thaw cycle method.

The results of the analysis presented in this paper should be treated as a preliminary stage of work on the development of an effective and reliable tool to predict the degree of concrete frost resistance. It is necessary to continue research in order to collect a larger number of observations (learning patterns) which will permit the verification of the model.

ACKNOWLEDGMENTS

The research has been partially provided under the POIG 01.01.02-10-106/09 project.

The paper was presented at the 8th International Conference AMCM 2014 – Analytical Models and New Concepts in Concrete and Masonry Structures (AMCM'2014), Wrocław, June 2014.

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