World Academy of Science, Engineering and Technology
International Journal of Civil and Environmental Engineering
Vol:16, No:12, 2022

Smart Technology for Hygrothermal Performance of Low Carbon Material Using an Artificial Neural Network Model

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***Abstract*—**Reducing the quantity of cement in cementitious composites can help to reduce the environmental effect of construction materials. Byproducts such as ferronickel slags (FNS), fly ash (FA), and waste as *Crepidula fornicata* shells (CR) are promising options for cement replacement. In this work, we investigated the relevance of substituting cement with FNS-CR and FA-CR on the mechanical properties of mortar and on the thermal properties of concrete. Foraging intervals ranging from 2 days to 28 days, the mechanical properties are obtained by 3-point bending and compression tests. The chosen mix is used to construct a prototype in order to study the material's hygrothermal performance. The data collected by the sensors placed on the prototype were utilized to build an artificial neural network.

***Keywords*—**Artificial neural network, cement, circular economy, concrete, byproducts.

I. Introduction

THE production of cement is increasing widely around the world due to the expansion of the construction sector and it produces a significant amount of CO_2. Multiple options for cementing systems have been stated. The partial replacement of cement by supplementary cementing materials presents a promising solution [1]. Cement can be partially replaced by different supplementary cementitious materials (SCM) such as blast furnace slag [2], FA [3], [4] and silica fume [3], [5], [6] and thus results in the valorization of industrial byproducts and the conservation of natural resources [7]. The enhanced use of SCM will lead to the reduction of CO_2 footprint. One of these products is FA, which is produced at large quantity [8]. Only a limited percentage is reused, the rest is treated as waste and is dumped and stored on the surface. This brings serious risks of air pollution and water contamination by leaching [3], [9], [10] due to their content of potentially toxic elements. Among these elements, we find Cu, Zn, As, Pb, Cd, Ni, B and Hg which constitute a serious threat to human health and to our ecosystems.

The heat and moisture transfers in porous building materials and envelopes is a complex phenomenon, and its relative impact is proven to be influenced by many factors including the climatic conditions and the hygroscopic properties of the material. Several models were used to simulate the hygrothermal behavior of concrete using a physical model with Wufi tools [5], [11] or black box models with ANN models [12]-[14]. We found only three works on the use of ANN models for the hygrothermal simulation at the wall scale [12]-[14]. For this reason, our interest is focused on data-driven model to simulate the heat and moisture transfer of an experimental cell. Indeed, data-driven approaches are well recognized for their outstanding performances to describe the behavior of a system. The simulation of the hygrothermal performance by ANN models will be executed without any physical knowledge, in contrast to what is implemented into Wufi tools. That is possible because we compute the numerical model with data collected from the system investigated.

II. Supplementary Cementing Materials

A. Fly Ash

FA as a byproduct of coal combustion is a heterogenous material. The chemical properties of FA are influenced both by the characteristics of the coal burned and by the storage method. The addition of FA to the concrete has an impact on its behavior. The use of FA as supplementary material leads to the reduction of the hydration heat and enhancement of the concrete mixtures' fluidity at the fresh state [3], [10]. The setting time of cementitious mixes including FA is longer than the mixes without FA. This difference is due to the slow pozzolanic reactions of FA [3], [15]. Rashad shows that the increase of the substitution rate led to a decrease of the drying shrinkage [3]. These findings are attributed to the densification of the matrix, which hinders the evaporation of water [15]. Concerning the thermal behavior of mixtures containing FA only few studies have investigated it. Nevertheless, it has been observed a reduction in the thermal conductivity of the mortar and concrete with FA [16]. The hydration reaction of FA is relatively slow, which explains why its contribution is not noticeable at younger ages [17]. Berry et al. [18] reported that the FA in the early stages act as a space filler, and that are implicated in the creation of ettringite (AFt). In the long term, they take part to the hydration reaction mainly as silico-aluminate binders. When materials rich in silica (SCM) are used, the reaction products,

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mainly in the form of Calcium Silicate Hydrates (CSH), show lower calcium-silica ratios (c/s) [19], [20]. Due to its slow hydration and necessity for activation, the use of FA in blended cement can improve age strength but lower early age strength. To improve the strength of ternary mixed cements at an early stage, efforts have been undertaken to incorporate carbonate. Different studies show that the combination of calcium carbonate, originating from limestone and FA in concrete or mortar is complementary. Indeed, the calcium carbonate filler improves the early strength of concrete whereas the FA improves the later strength and thus achieving an optimal strength development [19], [21].

B. Ferronickel Slags

The FNS used are provided by The Société Le Nickel (SLN, New Caledonia) and have interesting properties such as low density, sufficient hardness and toughness, strong compaction potential, high water permeability, and great fire resistance with moderate thermal expansion [22]. SLN produces 3 million tons of FNS per year and has a stock of 25 million tons [22]. Only 8% of yearly FNS production is currently being utilized [23]. FNS have been shown to be unsuitable for structural usage in research over the last 50 years [23], [24], and there are just a few investigations on the use of FNS from New Caledonia in concrete. However, issues with durability have been reported [25]. As a result, the FNS are only used as a base filler for roads [25].

C. Seashell Powder

Seashell is another potential waste product abundant in nature that can play the role of MSC. In Normandy (France), for example, scallops, oyster shells, crepidula, and mussel shells are available at high quantities. France is one of the largest consumers of shellfish in Europe. Each year, 191,800 tons of shells end up in landfills, incinerators or as waste in the coast in France [26]. Different studies on the use of shells as supplementary cementing materials have been ongoing for the past 50 years [27], [28]. These studies show that ground shells can be used in mortar and concrete. The partial replacement of cement by shells can present an adequate and lower thermal conductivity than the control mortar. The shells are composed of 95% of calcium carbonate ($CaCO_3$), which is similar to the calcium carbonate content of the limestone powder used for Portland cement production [29].

III. Result and Discussion

In line with what is already proposed in the literature, the conceptual study plan of our work consists of three main parts, summarized as follows: In the first step, we substituted partially the cement by FNS and crushed CR and by FA and crushed CR and we investigated the mechanical behavior, in particular the compressive strength according to EN196-1 [30]. In the second step, we investigated the thermal conductivity of the mixed concretes with cement substitution by FA-CR. In the third and last step, we studied the hygrothermal behavior of the material.

A. Compressive Strength

The compressive strength values of the mortars after a curing time of 2 days,7 days, 14 days and 28 days are presented in Figs. 1 and 2. For the mixes with cement substitution by FNS-CR (Fig. 1), the maximum compressive strength is observed for FNS-CR-10 and at the early age of 2 days. However, the compressive strength of mortars containing up to 20% FNS-CR is still more than half that of CM mortars. For the mixes with cement substitution by FA-CR (Fig. 2), the maximum compressive strength is obtained with 10% of cement replacement. Above 10% of FA-CR substitution (FA-CR-10), the results show that the compressive strengths decrease with the increase of the substitution rate. At a substitution level of 40%, the strengths are still adequate for application in the construction industry.

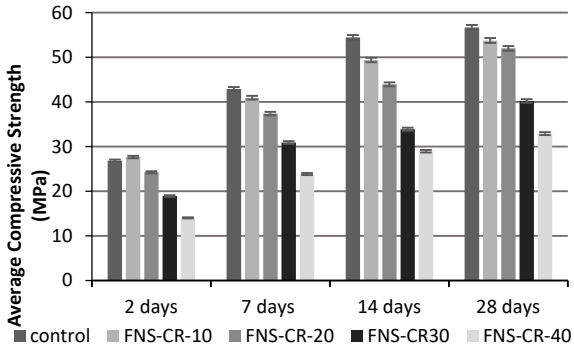

Fig. 1 Compressive strength of cement mortars with partial substitution by FNS-CR at 2, 7, 14 and 28 days

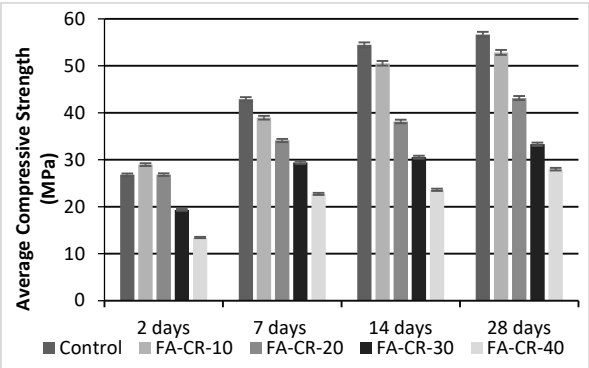

Fig. 2 Compressive strength of cement mortars with partial substitution by FA-CR at 2, 7, 14 and 28 days

B. Thermal Conductivity

The thermal conductivities of all the FNS-CR mix are close and do not decrease, for this reason we have chosen to present only the results of the FA-CR mixtures. Indeed, the concrete with FNS contains a large amount of Mg and Fe, which are very high-electronic-conductive elements.

For each substitution rate by FA-CR, a concrete specimen with dimension of 30 cm x 30 cm x 7 cm was prepared. The thermal conductivities of all mixtures were performed using a Heat Flow Meter (HFM). In Fig. 3, we show that the thermal conductivity of concrete samples decreased with the increase of

FA and CR amounts. The decrease in thermal conductivity between the control concrete and the concrete with 10% of FA-CR is greater than the decrease noticed above 10% of substitution level. These initial results are of great interest and show that the addition of FA and CR can significantly reduce the thermal conductivity of concrete.

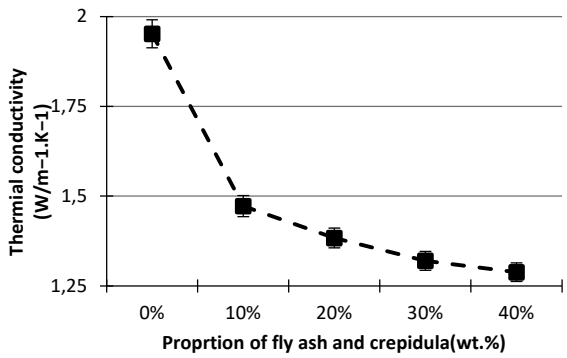

Fig. 3 Variation of thermal conductivity of different formulations after 28 days of cure

C. Artificial Neural Network

Finally, we used the FA-CR-30 optimal formulation for the rest of the study. Indeed, this mix has a mechanical strength similar to a CEM III 32.5 cement as well as a thermal conductivity, e.g., 30% lower than the ordinary concrete. To monitor the hygrothermal behavior of this formulation we built a prototype house of 70 cm long, 70 cm wide and 70 cm high (Fig. 4). The walls are made of 5 cm of concrete and 5 cm of external thermal insulation. As part of the reflective approach of recycling, we used panels of recycled cotton as insulation with a thermal conductivity of 0.039. We designed an opening of 30 cm × 25 cm to comply with the RE 2020 standard, which states that a Glazing of at least 16% of the living area must be applied [32]. In addition, we placed seven sensors of temperature and relative humidity, and one solar radiation sensor on different sides of the structure. Outside, we placed a temperature, a humidity, and a solar radiation sensor.

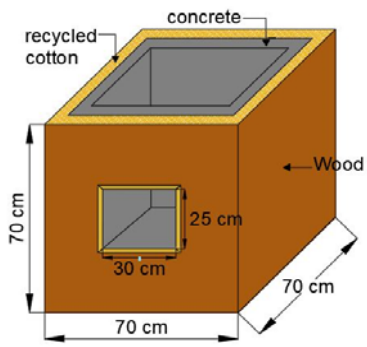

Fig. 4 Description of the prototype house

The data collected for 10 days from the sensors were used to train the data-driven model. The first step of the training is to choose the type of data that will enter the model training. Among the input data used, we have the outdoor temperature, outdoor humidity and the concrete constituents. The outputs are the temperature and humidity inside the structure. We trained the model with 70% of the collected data and tested it with the remaining 30%. Fig. 4 shows the temperature and the relative humidity obtained by the neural network model as a function of the experimental values during the training, validation and global phases. The adequacy of the result predicted by the implemented model was evaluated by the statistical correlation coefficient (R) (Fig. 5).

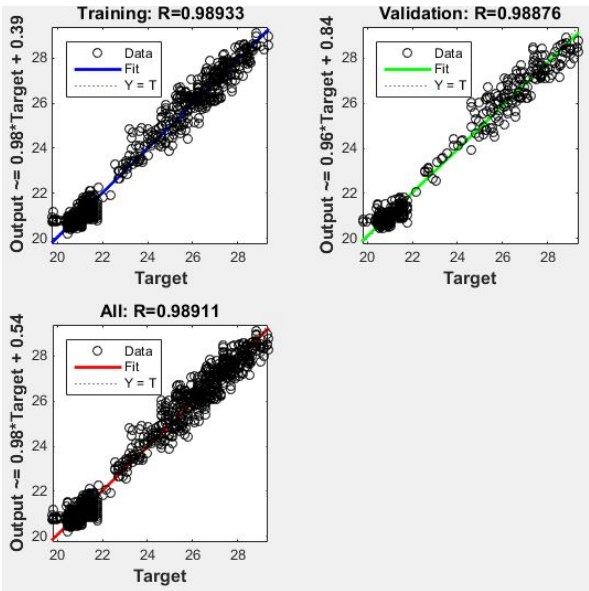

Fig. 5 Forecasted and experimental temperature values obtained for each phase of the model implementation

The statistical correlation coefficient is shown for each of the training, validation, and global phases. For the temperature prediction, we observe that the correlation coefficients for the training and validation data are 0.989 and 0.988 respectively. This result means that the estimated value from the input data agrees with the measured value.

D. Condensation

The Glazer technique is used to calculate the vapor pressure (Pv) and the internal saturation pressure (Ps), as stated by [31]. The area of the prototype where (Pvint-Psint) is maximum presents the greatest risk of condensation and there is no risk of condensation if (Pvint-Psint) is always negative or equal to zero. Fig. 6 shows the condensation risk indicator, which is a function of the internal (Pv) and internal (Ps). In Fig. 6, it is observed that there is no risk of condensation inside the prototype since the Pvint-Psint values are consistently negative. This is due to the moisture absorption by the concrete mixture with FA-CR.

Fig. 7 shows the compressive strengths of the concrete mixture with FA-CR-30 after 14 days, 28 days, and 300 days of curing time under controlled conditions. The compressive strength continues to increase with the age, this occurs due to the ongoing hydration of the cement. Indeed, by forming additional CSH and CSAH, the absorbed moisture contributes

to the continued pozzolanic reaction of the concrete.

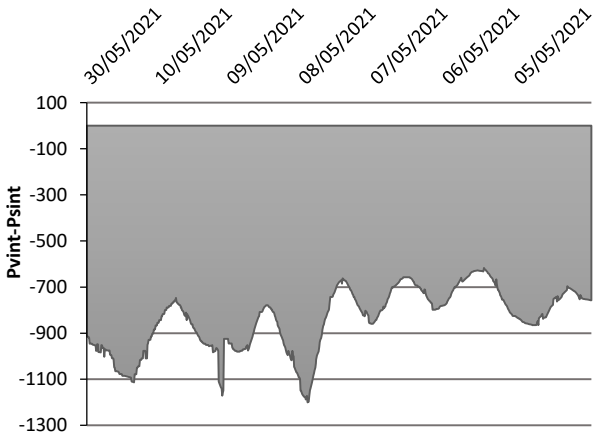

Fig. 6 Risk of condensation

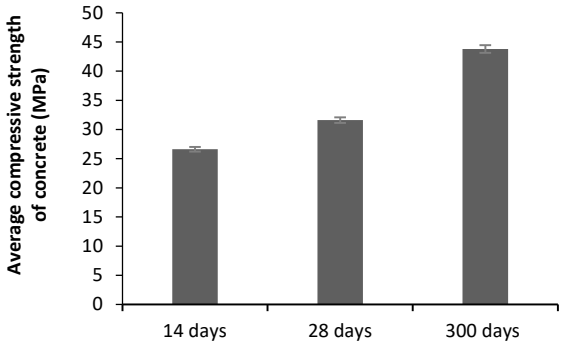

Fig. 7 Compressive strength at 14, 28, and 300 days of the concrete CR-FA-30

IV. Conclusion

The use of CR, FNS and FA will contribute in the accomplishment of sustainable development goals and in the reduction of carbon footprint. Our results show an acceptable behavior of the compressive strength with the substitution of cement by FNS-CR, and a significant improvement of the mechanical performance at 10% of cement substitution with FA-CR. Regarding thermal conductivity, we observed a significant decrease with the substitution increase. Based on the mechanical and thermal properties, the optimal formulation retained is with 30% of cement substitution. Then we evaluated the ability of the ANN model to predict the indoor temperature and relative humidity of the optimal concrete mix. The obtained coefficient of correlation is close to 1, which demonstrate a high accuracy of the neural model. Modeling with neural networks has proven to be a successful approach for achieving a good match between experimental and forecasted values.

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