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Optimizing the durability and service life of self-consolidating concrete containing metakaolin using statistical analysis

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HIGHLIGHTS

- An optimum SCC mixture containing MK was determined and evaluated.
- The most significant factors affecting the chloride permeability were obtained.
- Linear relationship between RCPT and chloride diffusion coefficients was found.
- Prediction models for estimating the long-term properties of SCC were developed.
- Different percentages of decline of permeability versus time were warranted.

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ABSTRACT

This paper utilizes the statistical design of experiments approach to optimize the mixture design of self-consolidating concrete (SCC) incorporating metakaolin (MK). The factors studied were total binder content, percentage of MK, water-to-binder ratio, and curing conditions. The results obtained from the developed statistical models were exploited to determine the most significant factors affecting the chloride permeability and the expected service life (calculated using Fick's second law of diffusion) of the tested mixtures. The developed models were also used to optimize the level of each response variable to minimize the chloride permeability, and to maximize the expected service life of the developed high performance SCC mixture. The results yielded an optimum SCC mixture with MK which achieved the lowest chloride permeability compared to counterpart SCC mixtures containing fly ash, slag, and silica fume. The results also showed that MK replacement proved to be the most significant variable affecting the chloride permeability, decline of permeability over time, and the service life of the tested mixtures.

1. Introduction

The production of self-consolidating concrete (SCC) is normally achieved by: (a) increasing the quantity of fines in the mixture, which could be done by incorporating one or more supplementary cementitious materials (SCM's) [1–3]; (b) adding high range water reducer admixtures (HRWRA), and if necessary, viscosity modifying admixtures (VMA) [4–5]; and/or (c) decreasing the coarse aggregate content in the mixture [6–7].

Different SCM's have been successfully used in the production of SCC, such as fly ash, ground granulated blast furnace slag, volcanic ash, cement kiln dust, rice husk ash, and silica fume [2]. Metakaolin (MK) is another type of SCM that is considered relatively new; it has been widely used for the production of high strength and high performance concrete over the past two decades [8]. In recent years, MK was introduced for the production of SCC. The behavior of MK in SCC mixtures was found to be similar to that in normal concrete mixtures, which showed an enhancement of the overall mechanical and durability performance [5].

Unfortunately, the production of SCC usually warrants a high cost, which is attributed to the high cement contents, high percentage of SCM's, and/or high doses of HRWRA. For this reason, optimizing SCC mixtures is vitally required to minimize the cost while maintaining the best fresh and hardened properties of the mixture. Statistical design of experiments is a useful tool that can be used to optimize the mixture components of SCC. Additionally, prediction models can be developed to evaluate the

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response at different levels of the governing factors. By using such models, the numerical optimization can then be performed to minimize or maximize the response [9–10]. Statistical design of experiments has been widely used in the mixture design and optimization for both normal concrete and SCC specially those containing SCM's [9–10]. Alternative soft computing methods are also applied to develop prediction models for different concrete properties. Examples of these methods are: artificial neural networks [11], genetic algorithm [12], and adaptive neuro-fuzzy inferencing systems [13]. However, most of these models require previous knowledge database about the input and output parameters along with significant mathematical work for the development of prediction relationships [13]. To this date, researchers apply the statistical design of experiments technique to analyze, model, study interaction between parameters, design, and optimize the behavior of SCC mixtures [14]. Durability and service life of concrete structures are considered to be the most important properties that need to be accounted for when optimizing SCC mixtures. Reinforced concrete structures, especially those subjected to high percentages of chlorides, should be given a special design consideration to extend their service life by reducing the corrosion of their embedded reinforcing steel [15–17]. The corrosion occurs when the chlorides from deicing salts, groundwater, or seawater penetrate the concrete cover and reach the reinforcing steel. Once the percentage of the chloride around the steel bar exceeds the threshold needed for corrosion initiation, the corrosion starts and rapidly propagates through the entire steel bar, leading to a mass loss and delamination of the concrete cover [17].

Chloride permeability is a significant property of concrete representing its service life. The assessment of the chloride permeability in concrete is usually performed using one of the following standard tests [18–19]: rapid chloride penetration test (RCPT) (ASTM C1202) and/or chloride bulk diffusion test (ASTM C1556). Most of the models used for predicting the corrosion initiation time account for the resistance of concrete to chlorides [16,20]. Concrete with low permeability and dense microstructure is proved to have more resistance to chloride ingress and longer time for corrosion initiation [17,21].

Recently, different methods were developed for predicting the service life of concrete structures. These methods usually monitor the service life of concrete structures in two periods, including initiation and propagation periods. The initiation period is the period in which the chlorides penetrate the concrete cover until they reach a threshold level (enough to initiate corrosion) at the rebar surface. The propagation period starts after the initiation period and ends when significant damage occurs in the structure resulting in cracks and rebar mass loss. The time of the initiation period is calculated using a simplified Fickian diffusion approach assuming that the chloride diffusion is the dominant mechanism of rebar corrosion. The time of the propagation period, however, depends on the definition of "significant damage." This level of damage in general varies depending on the requirements of the owner and the nature of the structure.

The main objective of this study was to develop an optimum SCC mixture incorporating metakaolin using a statistical design of experiments approach. The total binder content, percentage of MK, water-to-binder ratio, and curing conditions were varied to obtain the best mixture in terms of chloride permeability (RCPT and chloride diffusion), and extended service life. The statistical design of experiments approach was also used to present the most significant factors affecting each response variable in the mixture and to develop some prediction models for each test result. The study also presented a relationship between the different methods of assessing the chloride permeability in concrete for predicting the chloride diffusion of SCC mixtures containing metakaolin.

2. Research significance

Statistical prediction models can be used to predict the long-term behavior of SCC mixtures in terms of affecting variables. These models can be used to optimize the level of each variable and to minimize and/or maximize the responses of SCC mixtures. However, the available models in the literature are limited for SCC mixtures containing specific SCM's, such as FA, SF, and SG. As a result, a statistical optimization of SCC mixture containing MK was deemed necessary. The findings obtained from this investigation are of special interest for engineers applying MK in the production of SCC mixtures.

3. Experimental procedure

A total of 27 SCC mixtures were tested in this investigation. Twenty mixtures were used to optimize the mixture proportions of SCC using a statistical design of experiments approach, and 7 mixtures were used in the stage of validating the developed models. The 20 mixtures were designed by applying the Box–Wilson central composite design (CCD) method [22]. Three factors varied throughout the 20 mixtures, including the total binder content (A = 400–500 kg/m^3), water-to-binder ratio (B = 0.35–0.45), and the percentage of cement replacement by MK (C = 0–25%). The coarse-to-fine aggregate ratio was kept constant for all 20 mixtures as 0.9. The amount of HRWRA was determined based on maintaining a target slump flow of 650 ± 50 mm as per ASTM C1611 [23]. The slump flow diameter was fixed at this presumed value to ensure that all tested mixtures can achieve acceptable similar fresh properties for SCC. The amount of HRWRA required for each mixture to achieve the target slump flow was firstly determined based on testing some trial mixtures under similar mixing procedure. It should be noted that the HRWRA dosage was not considered as an independent variable in this study. The HRWRA dosage was only used to maintain a constant slump flow in all SCC mixtures. The reason behind that was if the HRWRA dosage was simultaneously varied as an independent factor with other mixtures ingredients, it would have yielded some unacceptable SCC mixtures with significantly varied values of slump flow.

After completing the fresh properties tests of the 20 mixtures, 100 mm (4 in) diameter × 200 mm (8 in) length cylinders were cast and cured for a maximum period of 180 days. These cylinders were used to prepare the samples of the RCPT and chloride diffusion tests. Two curing regimes were used: the first regime was to submerge the samples in water for 180 days, while the second regime was to store them in air for the whole 180-day period. Both regimes were performed at a controlled temperature of about 23 °C. After the 28-day curing period, the RCPT and chloride diffusion tests were performed on both air- and water-cured samples according to the standard tests ASTM C1202 [18] and C1556 [19], respectively.

The RCPT test was replicated at 90 and 180 days to measure the decrease in the chloride permeability versus concrete's age defined as the diffusion decay index (m). Using the values of m for each mixture and the chloride diffusion coefficients (D_a) obtained from the chloride diffusion test, the service life of the 20 mixtures were predicted by means of Fick's second law of diffusion.

A statistical analysis was performed on the results obtained from each test (RCPT and D_a tests), then the most significant factor affecting each response variable was determined, and prediction models for each test (response variable) were developed. The statistical analysis was completed by commercially available software for the design and analysis of experiments. These models were used to determine the optimum level of each factor by applying the numerical optimization tool.

The next stage used the numerical optimization tool to determine one optimum mixture proportions that achieved the best durability, and longest service life. In this stage, two SCC mixtures, including the optimum SCC mixture and another selected SCC mixture, were tested for validating the prediction models by comparing the results obtained from the models and the actual tests. Meanwhile, three additional SCC mixtures containing fly ash (FA), slag (SG), and silica fume (SF), as well as two normal concrete (NC) mixtures without any SCM's, were also tested and compared to the optimum SCC mixture.

3.1. Materials

In this program, type GU Canadian Portland cement, similar to ASTM Type I [24], with a specific gravity of 3.15, was used for both NC and SCC mixtures. The MK used in this research was delivered from the Eastern United States by Advanced Cement Technologies, conforming to ASTM C618 Class N [25], with a specific gravity of 2.56. The SG and SF used in this investigation have specific gravities of 2.89 and 2.27, respectively. FA conforming to ASTM C618 Class F [25] was employed in this project, with a specific gravity of 2.26. The chemical properties of cement and all SCM's are shown in Table 1.

A high range water reducer admixture (HRWRA), similar to ASTM Type F [26], was applied to achieve the required slump flow of SCC mixtures. The specific gravity, volatile weight, and pH of the HRWRA were 1.2, 62%, and 9.5, respectively. Natural sand was used for the production of the SCC mixtures with specific gravity of