様　式　C－１９、F－１９－１、Z－１９　（共通）

科研費 KAKENHI

科学研究費助成事業　　研究成果報告書

令和　３ 年　６ 月　７ 日現在

機関番号：１２６０１
研究種目：若手研究
研究期間：2019～2020
課題番号：１９Ｋ１５０５９

研究課題名（和文）Characterising and modelling the chloride resistance of blended-cement concrete by considering the effect of supplementary elements from glass

研究課題名（英文）Characterising and modelling the chloride resistance of blended-cement concrete by considering the effect of supplementary elements from glass

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交付決定額（研究期間全体）：（直接経費）　3,200,000円

研究成果の概要（和文）：本研究は、SCM材料を用いたコンクリート構造物の鉄筋腐食モデルの構築に関する研究である。アルミノシリケートガラスの溶解速度は、その化学組成とガラス相の準結晶ナノドメインに依存し、また、SCMの塩分抵抗性は，細孔構造および細孔溶液中の塩化物イオンと化学結合した塩化物との間の静電気的相互作用に依存することが明らかになった．その結果、SCMsを用いたコンクリート構造物における荷重作用、塩分の浸透、ひび割れの発生、腐食の開始および進行の強連成による鉄筋腐食予測モデルを提案し、その有用性を確認するとともに、SCMを用いることでコンクリート構造物の耐久性を大幅に改善できることを確認した。

研究成果の学術的意義や社会的意義
Utilization of SCMs is one of the most promising to improve durability of concrete structures. This research studies the reactivity of SCMs and chloride resistance of SCMs blended cement paste. A probability model for assessing corrosion failure of concrete structures was developed for engineers.

研究成果の概要（英文）：This research studied the dissolution rate of SCMs through synthetized aluminosilicate glass. The dissolution rate of aluminosilicate glass depends on its chemical composition and quasi-crystalline nanodomains of glass phases. The chloride resistance of blended cement paste depends on the microstructure and the electrostatic interaction between the chloride ions in the pore solution and the chemical bound chloride. A probability model was finally proposed, which considers the coupled effect of loading action, chloride ingression, crack development and corrosion initiation and progression. The analyses results show that SCMs could improve the durability of concrete structures. This probability model provides a powerful tool for civil engineer to design concrete structure under marine environment.

研究分野：Civil Engineering

キーワード：SCMs　Chloride　Aluminosilicate glass　Probability analyses

1. Background

Reinforcement corrosion is one of most dangerous threats to reinforced concrete (RC). An enormous amount of money is spent each year to maintain RC structures. The Japan Society of Corrosion Engineering has estimated that the economic loss induced by reinforcement corrosion of RC structures rose to 207 billion yen from 1996 to 1998. The ingression of environmental chloride from de-icing salt or sea-water is one of the most dominant factors contributing to corrosion. Therefore, engineers have attempted to improve the chloride residence of concrete. Among the various measures being explored, the use of SCMs is one of the most promising. In addition to improving the casting quality, SCMs also enhance the microstructure of cement paste and mitigate chloride attack from the environment. Thomas et al. studied chloride concentration profiles at different ages in fly ash concrete exposed in a marine tidal zone for up to 10 years. The chloride content barely increased beyond the initial 28-day period for the concrete with 30% fly ash. Unfortunately, the application of SCMs is still hindered by their significant variability. Therefore, engineering practice demands a unified and comprehensive method to characterise the chloride resistance of blended concrete and design SCM blended concrete structure.

2. Purpose

This research aims to characterize of the reactivity of SCMs through synthesised glass; study the underlying mechanisms of chloride resistance of SCMs blended cement paste; and develop a comprehensive chloride transport model. A probability model for assessing corrosion failure of concrete structures was further developed. This probability model facilitates the development of a comprehensively whole-life designed approach of concrete structure under marine environments.

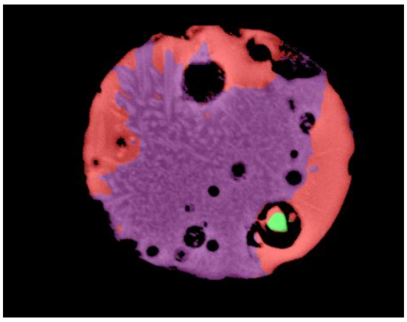
3. Research methods

This research studied the reactivity variations of SCMs through synthesised glass with various Ca/Si ratios and Al/Si ratios. The effects of chemical composition and quasi-nanodomains of glass phase on the dissolution rate of SCMs was discussed. The chloride-resistance of blended-cement paste were studied by steady-diffusion test. The effect of Ca/Si and Al/Si ratio was studied by mixing various mass fractions of nano SiO_2 and Al_2O_3 powder. Based on these experimental results, a probability model for assessing corrosion failure of concrete structures was finally developed, which considers the coupled effect of loading action, chloride ingression, crack development and corrosion initiation and progression.

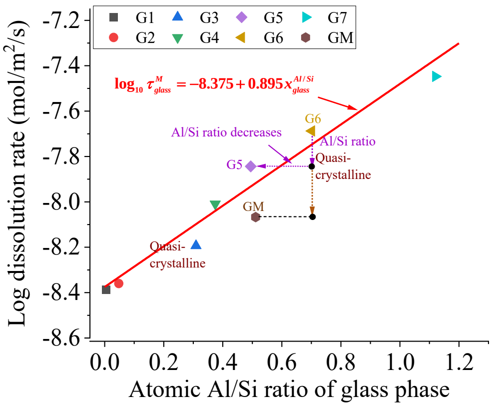
4. Research results

4.1 Dissolution rate of aluminosilicate glass

Aluminosilicate glass with various Al/Si ratios were synthetized. All samples were prepared using reagent-grade Al_2O_3, SiO_2, $CaCO_3$, Na_2CO_3 and MgO. The mixtures with different Al/Si ratio were designed according to chemical composition of low-calcium SCMs. The samples were then heated to 1600 °C and maintained at that temperature for 4 h to ensure that the powders completely and homogeneously melted. The molten mixtures were then removed and quenched in deionised water. A model glass-mullite mixture (Fig. 1a) was synthesized using the sample mixture of G6 but quenched in air to allow crystallization of mullite.



(a) Glass-mullite intermixture found from fly ash



(b) Dissolution rate of aluminosilicate glass

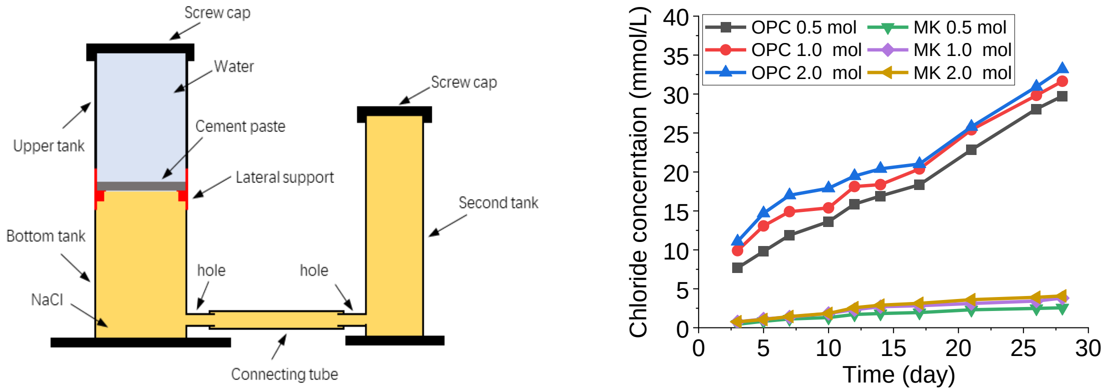
Fig. 1 Synthesized Aluminosilicate glass and dissolution rate result

The long-term dissolution rates of aluminosilicate glass were determined under alkaline conditions by measuring dissolved element concentrations (Fig. 1b). Experimental results show that the dissolution rate of aluminosilicate glass depends on its Al/Si ratio due to the non-bridging oxygen increasing and phase separation. Experimental results also show that the dissolution rate of glass-mullite intermixture is significantly smaller than the aluminosilicate glass with same chemical composition. That is because the Al/Si ratio of glass phase of glass-mullite decreases and quasi-crystalline nanodomains form in the glass phase.

4.2 Steady chloride diffusion test

Several blended cement pastes were prepared by white cement and nano SiO_2 and Al_2O_3 with a water-binder ratio of 0.55 and a replacement ratio of 10%. The mass fractions of nano SiO_2 and Al_2O_3 were adjusted according to the chemical composition of silica fume, fly ash and metakaolin. The cement pastes were cured at RH 99% for 120 days. The pozzolanic reaction were believed to be completed because nano powders were used. After curing, all cement pastes were polished to 3mm height and installed on a customized experiment setup of steady chloride diffusion (Fig. 2a). The chloride concentrations of bottom tank were 0.5mol/L, 1.0mol/L and 2.0mol/L. The chloride concentrations of upper tank due to diffusion were measured by ion meter.

Experimental results shows that the diffusion coefficient of blended cement paste is significantly smaller than the one of cement paste. That is because the microstructure of blended cement paste is enhanced due to the pozzolanic reaction and the formation of Friedel's salt. It should be noted that the chloride concentration of upper tank does not proportionally increases with the one of bottom tank. That is because the electrostatic interaction between the chloride ions in the pore solution and the chemical bound chloride on the surface of C-(A)-S-H gel, which so called electrical double layer (EDL). A more comprehensive chloride transport model of blended cement paste is developing based on Al/Si ratio and Ca/Si ratio. This model considers the microstructure of blended cement paste and the effect of chloride binding and EDL.



(a) Experiment setup of steady chloride diffusion (b) steady chloride diffusion results

Fig. 2 Experiment setup of steady chloride diffusion and chloride diffusion results

4.3 Cement chemistry analyses of blended cement paste

Reliable cement chemistry analysis approaches are required to characterize the chloride resistance of blended cement paste. This research developed a modified tangential method for thermogravimetric analysis test. This method provides a reliable estimation of calcium hydroxide content and chemical water content of blended cement paste. This research also developed a method to measure the Ca/Si and Al/Si ratio of blended cement paste based on SEM-EDS. Fig.3 shows these two developed methods.

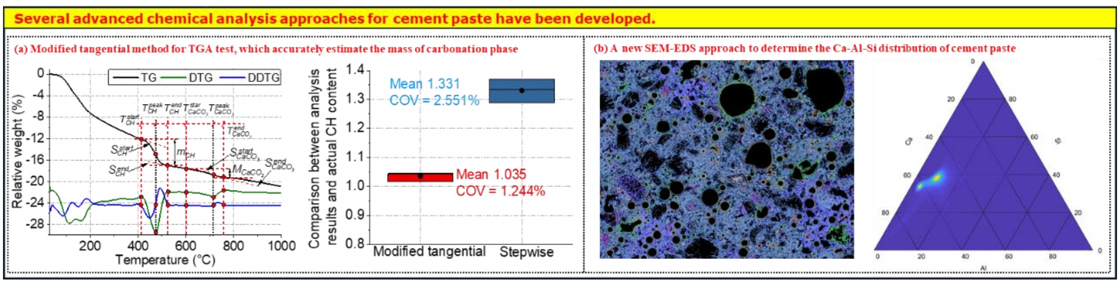


Fig. 3 Advanced chemical analyses approach for blended cement paste.

4.4 Probability assessment of corrosion failure time of concrete structure

A rapid approach of time-dependent chloride diffusion of two-layer material was developed. This approach could be used to simulate the chloride diffusion process of cracked concrete, which considers the crack development and time-dependency of chloride diffusion coefficient and surface chloride content. The reliability of this approach was verified through comparison with finite element method. It should be noted that the solution speed of this approach is very fast, only 0.2 sec for one case. It facilitates the probability assessment of corrosion failure of concrete structures.

Coupling with rapid two-layer diffusion approach, a probability model for assessing corrosion failure of concrete structures was finally developed, which considers the coupled effect of loading action, chloride ingression, crack development and corrosion initiation and progression. Based on the experimental result of steady chloride diffusion test, probability analyses of estimating corrosion failure time of cracked concrete beam were conducted using Monte-Carlo simulation. The designed details of concrete beam were illustrated in Fig. 4.

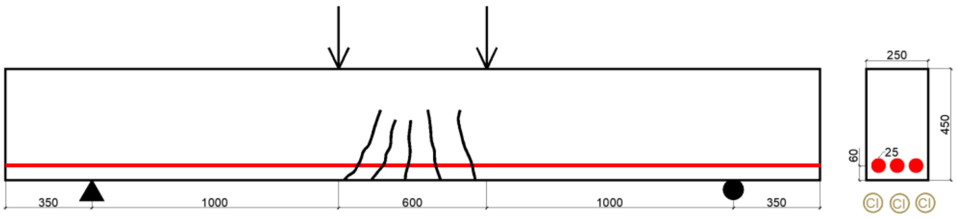


Fig. 4 Designed details of concrete beam

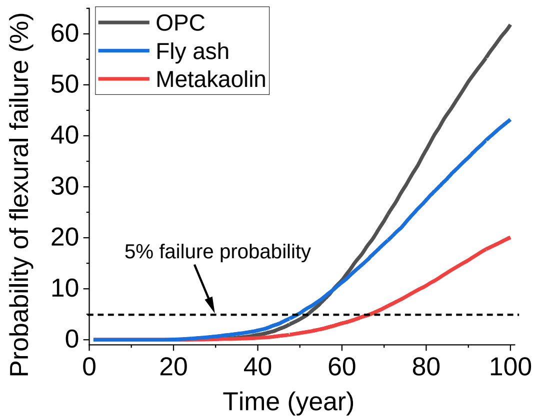


Fig. 7 Probability analyses results

It is assumed that the beam subjected 175kN, which is around 65% of the flexural capacity of the beam. The surface chloride content gradually increases from 2% to 5% (mass fraction of concrete powder). The DuCOM corrosion model was adopted. The concrete beam is assumed to be failed if the reinforcement stress is higher than yielding stress. The sample cases is 5×10^5. Fig. 5 shows the analyses result. It shows that flexural failure of OPC concrete beam appears after 20 year. The failure probability increases to 65% after 100 year. SCMs significantly improves the durability of concrete beam. The failure probability decreases to 43% and 20% when we use fly ash and metakaolin.

５．主な発表論文等

〔雑誌論文〕　計2件（うち査読付論文　2件／うち国際共著　2件／うちオープンアクセス　0件）

１．著者名 Wang Tiao、Ishida Tetsuya、Gu Rui	４．巻 243
２．論文標題 A study of the influence of crystal component on the reactivity of low-calcium fly ash in alkaline conditions based on SEM-EDS	５．発行年 2020年
３．雑誌名 Construction and Building Materials	６．最初と最後の頁 118227～118227
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.conbuildmat.2020.118227	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Wang Tiao、Ishida Tetsuya、Gu Rui、Luan Yao	４．巻 267
２．論文標題 Experimental investigation of pozzolanic reaction and curing temperature-dependence of low-calcium fly ash in cement system and Ca-Si-Al element distribution of fly ash-blended cement paste	５．発行年 2021年
３．雑誌名 Construction and Building Materials	６．最初と最後の頁 121012～121012
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.conbuildmat.2020.121012	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

〔学会発表〕　計1件（うち招待講演　0件／うち国際学会　1件）

１．発表者名 Wang Tiao、Luan Yao
２．発表標題 A probabilistic approach for estimating corrosion possibility of reinforced concrete structure considering crack development
３．学会等名 International RILEM Conference on Microstructure Related Durability of Cementitious Composites（国際学会）
４．発表年 2020年～2021年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計1件

国際研究集会	開催年
The International conference on simulation technology in Civil Engineering	2019年～2019年

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関