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科学研究費助成事業　　研究成果報告書

令和　６年　６月２６日現在

機関番号：１２４０１
研究種目：基盤研究(C)（一般）
研究期間：2019～2023
課題番号：１９Ｋ０４５４７

研究課題名（和文）Modeling and re-corrosion evaluation of patch repaired concrete subjecting to chloride attack

研究課題名（英文）Modeling and re-corrosion evaluation of patch repaired concrete subjecting to chloride attack

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交付決定額（研究期間全体）：（直接経費）　　3,400,000円

研究成果の概要（和文）：本研究では，塩害を受けた鉄筋コンクリートについて，断面修復後の塩分浸透挙動および再度腐食可能性の検討を行った．実験では，塩分浸透挙動において，電気泳動法を用い，断面修復材に発生したひび割れ，および混和材や撥水処理などの影響について定量的評価を行った。その結果，ひび割れ幅の増加に伴い塩分浸透係数が顕著に増加すること，および混和材と撥水処理による抑制効果が明らかになった．実験結果を踏まえ，ひび割れが発生した断面修復材の水と塩分浸透に関する数値解析を行い，鉄筋腐食の発生について評価を行った．解析結果により，ひび割れ幅や分布，残存塩分，はつり深さなどの要因が塩化物浸透と腐食に及ぼす影響を示した．

研究成果の学術的意義や社会的意義
Chloride penetration of patch repaired concrete is more complicated than normal concrete, because more factors are involved. Those factors were thoroughly studied, offering important insights for practice. In addition, the numerical approach considers those factors from academic viewpoints.

研究成果の概要（英文）：The research focuses on evaluating chloride transport and corrosion in patch repaired concrete subjected to chloride attack. Experimental investigations include studies on chloride migration in cracked repair mortars as well as the influence of incorporating supplementary cementitious materials (SCMs) and hydrophobic agents. These experiments evaluate factors such as crack width, repair material type, and surface treatments, revealing significant increase in chloride diffusion with increasing crack width and mitigation effect with SCMs and hydrophobic treatments. Numerical simulations using multi-scale models further explore water ingress and chloride penetration in cracked repair mortars. The obtained chloride amount in repaired concrete is used for evaluation of steel rebar corrosion initiation. The simulations provide insights into the influence of crack pattern on water absorption and chloride distribution, crucial for understanding long-term durability.

研究分野：コンクリート材料

キーワード：patch repaired concrete　repair materials　chloride migration　crack　multi-scale model　water repellency　corrosion　fiber reinforced mortar

１．研究開始当初の背景

Corrosion of steel reinforcement in concrete resulting from chloride attack is a critical issue that causes deterioration of structures. In Japan, large numbers of concrete structures in coastal or de-icing-agents applied areas have suffered chloride attack. For repairing those structures, patch repair is the most common method. It is to remove the chloride-contaminated part of concrete, remove the reinforcement rust, if necessary, and apply new material. The removed part of concrete may be partial or the whole cover concrete, or even include some concrete behind the steel bar.

After repair, however, new corrosion at early stage is reported for some structures. Typical corrosion often occurs at the bottom of steel reinforcement where the old concrete is remained. The reason is incipient anode formation in the old concrete because of different chloride content, permeability, and electrical resistivity in the old concrete and the repaired part. Another possible corrosion occurs in the new part if the permeability of repaired material is high, or micro-crack occurs due to restrained shrinkage. Facing to those repaired concrete structures, an appropriate modeling of the chloride transport and corrosion, and evaluation the risk of re-deterioration occurrence is important and requisite. Furthermore, even if early re-corrosion does not happen, evaluation of chloride transport and corrosion risk at long time is necessary for the life-span performance of the repaired structures.

２．研究の目的

The purpose of this research is to establish an approach for evaluating chloride transport and corrosion of patch repaired concrete subject to chloride attack. The key factors, including crack width, repair material type, hydrophobic treatment, and so on, are investigated and elucidated by experiment. Numerical models are established to reasonably reflect the roles of those factors. According to the result of numerical analysis, it is hoped to provide a reasonable evaluation for chloride penetration and the risk of re-corrosion of the repaired concrete. For patch repaired concrete, such researches are still lacked, but the work is very important from engineering viewpoint. This research aims to provide a foundation for such as evaluation.

３．研究の方法

(1) Experiment on chloride migration of repair mortar with the occurrence of cracks

Two types of specimens were prepared. One was the single repair mortar cylinder with the diameter of 100mm and height of 50mm. The other was two-layer specimen with the combination of repair mortar and substrate concrete, both of which had the diameter of 100mm and height of 25mm. A tensile splitting crack was introduced in the mortar part of both the specimens, controlling the crack width in the range of 0.02-0.35 mm (Fig. 1). For the two-layer specimen, after introducing the crack in mortar part, the substrate concrete was cast on one side of the mortar, imitating a real patch repair condition. Different repair mortar materials were used, including two types of acrylic resin mortar with low and high strength (AM-Low and AM-High) and one fiber reinforced cement mortar (FM). Steady-state migration test was performed to evaluate chloride penetration resistance of the specimens and the influence of crack width (Fig. 2).

Fig. 1 Cylinder specimens with an induced crack

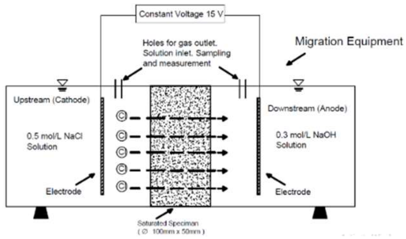


Fig. 2 Steady-stage migration test

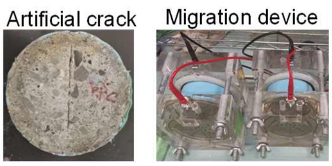


Fig. 3 Artificial crack and migration device

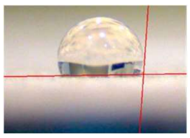


Fig. 4 Surface water repellency

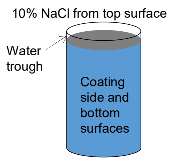


Fig. 5 Chloride penetration test

(2) Experiment on chloride migration of cracked mortar with SCMs and hydrophobic agent

In recent years, supplementary cementitious materials (SCMs) from industrial wastes or natural resources are being used in concrete materials more to achieve low-carbon emission. In this study, cement mortar with SCMs were also used as repair mortar, so the influence of cracks was also investigated by performing chloride migration tests. Five types of SCMs, including blast furnace slag (BFS), fly ash (FA), silica fume (SF), metakaolin (MK), limestone calcined clay cement (LC3), were used to partially replace ordinary Portland cement (OPC) in mortar with the replacement ratio of 20%. The specimen was cylinders with the diameter of 100mm and height of 50mm. A penetrating crack was introduced in the mortar by inserting a copper plate with the thickness of 0.1, 0.2, 0.4, and 0.6mm to form the same crack width (Fig. 3). Steady-state migration was also used to evaluate the chloride penetration resistance. In addition, the influence of surface hydrophobic treatment was also studied. For the above specimens, those using MK, FA, and BFS were then surface-treated by applying silane-based hydrophobic agent, showing high surface water repellency (Fig. 4). Steady-stage migration test was carried out again to evaluate the effect.

Bulk hydrophobic treatment on chloride penetration was also studied by mixing silicone oil in the mixture of mortar or preliminarily spraying it on the surface of sand. Cylindrical specimens with a diameter of 50 mm and a height of 70 mm were prepared and treated in bulk. Chloride penetration was carried out for seven days by applying 10% NaCl solution to the top surface of the specimens (Fig. 5). Subsequently, the specimens were sliced to conduct a chloride content analysis by potentiometric titration.

(3) Experimental study on chloride binding and migration of BFS-blended mortar with different slag ratios

This experimental focused on BFS-blended cement mortar because it has been widely reported to have high chloride resistance according to high chloride binding capacity and refined microstructure. However, the influence of BFS replacement ratio remains unclear. In the experiment, cement paste and mortar samples were made with BFS ratio at 0, 20%, 50%, and 70%. Hydrated cement samples were immersed in NaCl solutions with a series of concentration (Fig. 6). Chemical and physical bound chloride at equilibrium was determined using thermogravimetric analysis (TGA) and potentiometric titration against silver nitrate. Furthermore, steady-state migration test was performed using mortar specimens.

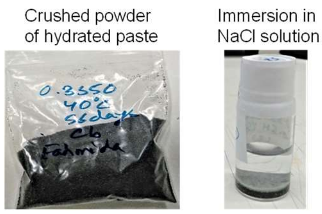


Fig. 6 Chloride binding test

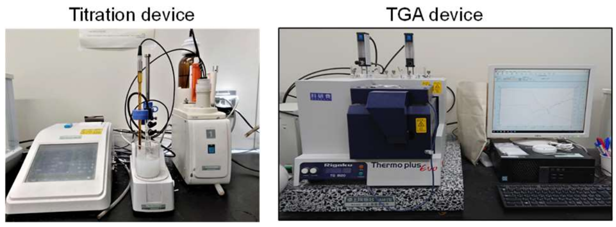


Fig. 7 Devices of titration and TGA

(4) Simulation of water ingress and chloride penetration based on multi-scale models

For water ingress of cracked mortar, a multi-scale approach for numerical simulation of the behavior is proposed by considering the detailed crack patterns such as the width and location of cracks (Fig. 8). Water flows in bulk matrix and multiple cracks are simulated using two individual transport equations. Water absorbed from a crack to its adjacent matrix is treated as the mass exchange of the two equations, taking into account pore structure and water status in the bulk matrix as well as the damage level of the crack surfaces. The multi-scale models were validated by performing numerical analysis on water absorption of an often-used repair mortar, strain-hardening cementitious composites (SHCC).

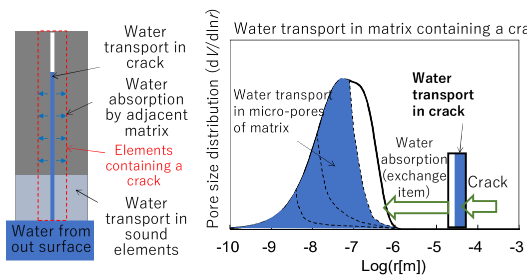


Fig. 8 Multi-scale water ingress model for cracked

For chloride penetration of repair mortar and patch repaired concrete, long term simulation was carried out using finite element method, based on the chloride penetration coefficients obtained from the above-mentioned migration tests. Different material and construction conditions were taken into account in the simulation, including the types of repair materials, crack width, depth of repair layer, remained chloride in the substrate, and so on.

４．研究成果

(1) Chloride migration of repair mortar with the occurrence of cracks

The influence of crack width on the effective chloride diffusion coefficient of repair mortar and two-layer specimens are shown in Figs. 9 and 10. For the single mortar cylinder (Fig. 9), the diffusion coefficient, in the absence of cracks, followed the order of AM-High < FM < AM-Low. It was found that lower diffusion coefficient corresponded to higher compressive strength, probably owing to the denser microstructure of higher strength cases. On the other hand, when cracks occurred, the diffusion coefficient increased with the increase in crack width for all repair mortar, and the influence of cracks was notably observed. Additionally, when using high-strength repair mortar (AM-High), the impact of cracks on chloride diffusion became more pronounced. For the two-layer specimens (Fig. 10), the results are consistent with those of the single-layer specimens. In the absence of cracks, AM-High exhibited the lowest diffusion coefficient, which means highest chloride resistance, while AM-Low exhibited the highest coefficient. As the crack width increased, the chloride resistance of all three types of two-layer specimens decreased.

(2) Chloride migration of cracked cement mortar with SCMs and hydrophobic agent

The influence of SCMs and artificial crack width are shown in Fig. 11 according to the migration test results. It can be found that, in the absence of cracks, compared to OPC, the effective diffusion coefficients of BFS, SF, FA, MK, and LC3 showed significant decrease. In the presence of cracks, it was found that the effective diffusion coefficient increased significantly with the increase in crack width for all types of binders. The influence of surface treatment using hydrophobic agent is shown in Fig. 12. It can be seen that in the case of surface treatment, the effective diffusion coefficients showed a downward trend.

One result of chloride penetration into the cement mortar with bulk hydrophobic treatment are shown in Fig. 13. The specimens were pre-dried at 20°C with 60% RH. For the case without treatment, the total chloride content at the 0-10 mm depth was 21.1 kg/m^3, whereas it was 4.3 kg/m^3 at the 20-30 mm depth, showing chloride penetration from the surface that was principally caused by the absorption of NaCl solution. The corresponding cases of direct mixing hydrophobic agent in the mixture and spraying it on sand preliminarily were 7.4 and 5.1 kg/m^3 at the 0-10 mm depth and below the lowest detectable level at the 20-30 mm one. The results indicate the effectiveness of bulk treatment against chloride penetration.

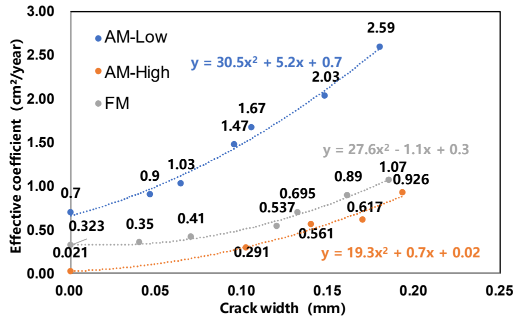


Fig. 9 Effective diffusion coefficient of single mortar specimens with steady-state migration tests

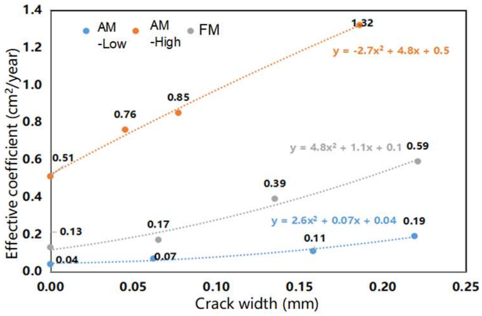


Fig. 10 Effective diffusion coefficient of two-layer specimens with steady-state migration tests

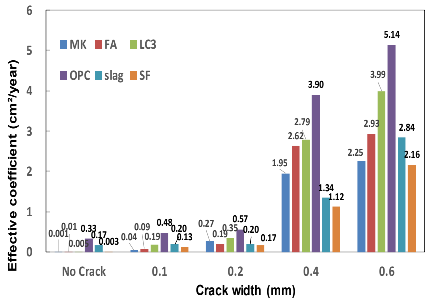


Fig. 11 Effective diffusion coefficient of repair mortar made from SCMs with steady-state migration tests

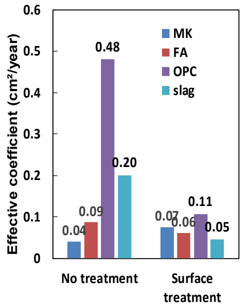


Fig. 12 Effective diffusion coefficient of specimens with surface treatment (0.1 mm crack)

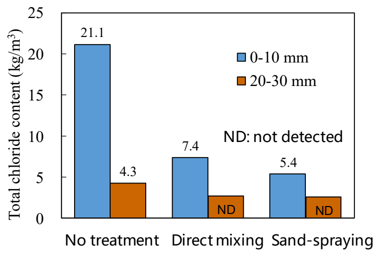


Fig. 13 Chloride penetration results for cement mortar with bulk treatment of hydrophobic agent

(3) Chloride binding and migration of BFS-blended cement mortar with different slag ratios

According to chloride binding test results, it was found that chloride binding capacity of BFS-blended cement pastes remarkably depends on the replacement ratio of slag in Portland cement. Fig. 14 shows an example obtained from the test by immerse the cement paste samples in 3.0 mol/L NaCl at 20 ˚C. In general, for all the cases, physically bound chloride accounts for around two third in the total bound chloride, whereas chemically bound chloride accounts for the remaining one third. In addition, the amount of totally bound chloride shows the order of 50% > 70% = 20% BFS > OPC. From the tests of reaction degree, the was discussed to be attributed to the different reaction degree of BFS in cement pastes. Moreover, W/B ratio also exhibited the noticeable effect on chloride binding, showing higher efficiency of chloride binding at relatively high w/b ratio.

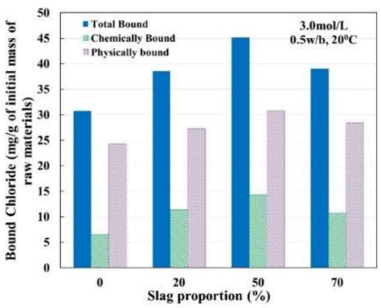


Fig. 14 Physically and chemically bound chloride of BFS blended mortar with different slag ratios

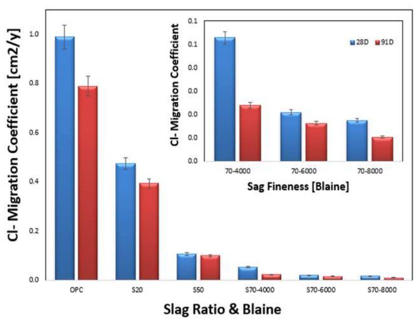


Fig. 15 Influence of slag ratio and fineness on chloride diffusion coefficient

The results of steady-state migration tests for BFS-blended cement mortars are shown in Fig. 15. It can be found that the trend is different from chloride binding capacity. The chloride diffusion coefficient decreased as a result of increment in BFS content and Blaine values. With 20, 50, and 70% BFS, the coefficient dropped by 48, 90, and 95%, for 28-day specimens, and 49, 87, and 98%, for 91-day specimens, respectively. Such drop could be attributed to lower Ca/Si ratio, higher tortuosity, and denser pore structure as a result of more slag incorporation. When finer slag with higher Blaine value was used, diffusion coefficient decreased further owing to higher reaction degree of slag.

(4) Simulation of water ingress and chloride penetration based on multi-scale models

Fig. 16 shows an example of simulating water absorption behavior of cracked SHCC materials, which was verified with test data from past studies. For the cracked cases, the water absorption in the analysis increases with increasing crack density in the range of 50 to 200 per meter, showing consistent trend with the tests. Water absorption is shown in contour plot in Fig. 17 for different crack patterns. The contours are consistent with past studies on water visualization of cracked SHCCs by neutron radiography.

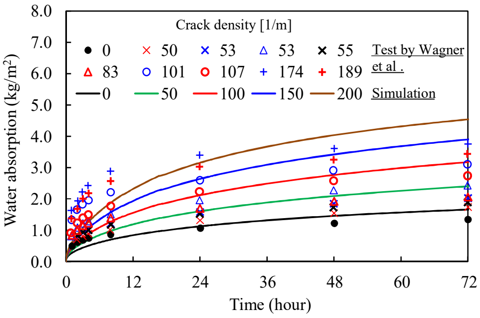


Fig. 16 Water absorption of cracked SHCC

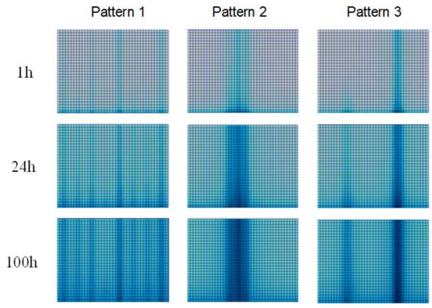


Fig. 17 Water absorption in contour plot for different crack patterns at 1, 24, and 100 hours.

Based on chloride diffusion coefficient obtained from the migration tests, long-term chloride penetration into patch repaired concrete were simulated. Fig. 18 show an example for patch repaired concrete with the occurrence of cracks in repair mortar ranging from 0 to 0.2 mm. It can be seen that chloride penetration is significantly accelerated with increasing crack width. When crack width is 0.2 mm. chloride amount at the interface between substrate concrete and repair mortar is higher to 7 kg/m^3. If taking the chloride amount corresponding to corrosion initiation as 3 kg/m^3, there is a high probability that corrosion of steel rebars takes place in the old concrete 40 mm deep from repaired surface. Other conditions were also simulated and discussed. The representative results are shown in Fig. 19. By increasing repair depth, chloride penetration in concrete structure is effectively mitigated so corrosion risk is remarkably reduced (Fig. 19 (a)). For repair mortar, BFS and polymer cement mortar (PCM) are more effective than the normal OPC mortar owing to lower chloride diffusion coefficients (Fig. 19(b)). Fig. 19(c) indicated the redistribution of the remained chloride in the repaired concrete after 30 years, even that there is no chloride penetration from external environment with surface coating. In addition, if chloride absorbent is added in repair mortar, chloride content can be reduced effectively.

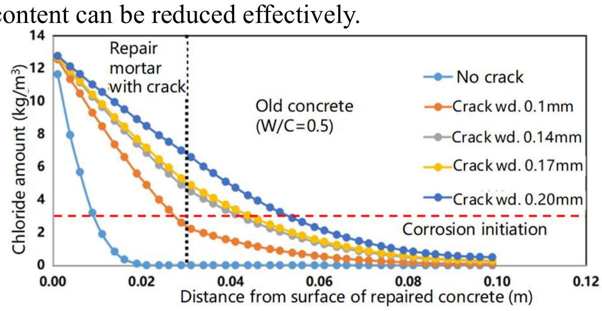
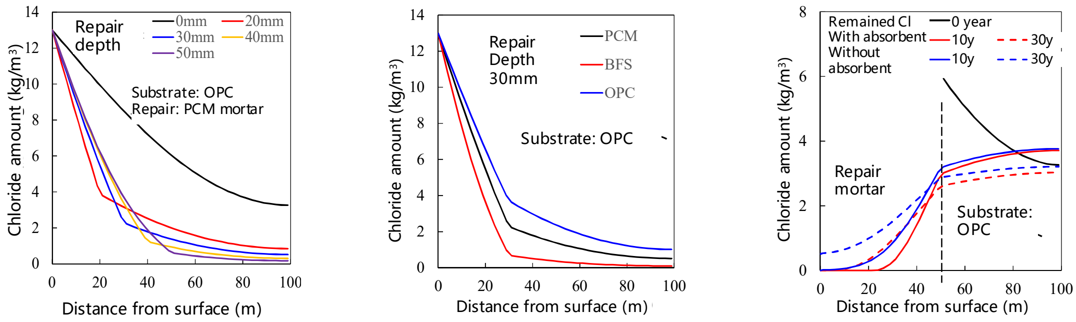


Fig. 18 Simulation of chloride penetration in repaired concrete with the occurrence of crack in repair mortar and evaluation of corrosion initiation (30 year)



(a) repair depth (30y after repair) (b) Repair mortar type (30y after repair) (c) Remained Cl

Fig. 19 Simulation of chloride penetration in repaired concrete for different conditions.

５．主な発表論文等

〔雑誌論文〕　計3件（うち査読付論文　3件／うち国際共著　1件／うちオープンアクセス　0件）

１．著者名 Parvin Fahmida、Luan Yao、Habirun Asiya Nurhasanah	４．巻 36
２．論文標題 Experimental Study on Chloride Binding of Slag-Blended Portland Cement with Different Slag Ratios	５．発行年 2024年
３．雑誌名 Journal of Materials in Civil Engineering	６．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.1061/JMCEE7.MTENG-17374	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 Luan Yao、Asamoto Shingo	４．巻 367
２．論文標題 Experimental study on mortar with the addition of hydrophobic silicone oil for water absorption, strength, and shrinkage	５．発行年 2023年
３．雑誌名 Construction and Building Materials	６．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.conbuildmat.2023.130323	査読の有無 有
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１．著者名 Luan Yao、Ishida Tetsuya	４．巻 54
２．論文標題 A multi-scale approach for simulation of capillary absorption of cracked SHCC based on crack pattern and water status in micropores	５．発行年 2021年
３．雑誌名 Materials and Structures	６．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.1617/s11527-021-01664-3	査読の有無 有
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3．学会等名 1st International Conference on Advances in Engineering and Technology for Sustainable Development (ICONS2023)（国際学会）	
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1．発表者名 Fahmida Parvin, Yao Luan	
2．発表標題 Study on chloride binding property of slag blended cement considering different slag blending ratios	
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〔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
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研究協力者	浅本　晋吾 (Asamoto Shingo)	埼玉大学・理工学研究科・准教授 (12401)	

７．科研費を使用して開催した国際研究集会

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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			
バングラデシュ	Chittagong Univ. of Engr. & Tech.			
インドネシア	Muhammadiyah Univ. of Sumatra			