Study on Implementation of CO_2 Fixed Pervious Concrete Pavement

Hiroshi Fujii [1], Kazuhiro Yamauchi [2], Yoshiyuki Suzuki [3], Takahiro Iwafuchi [3],
Toshihiro Yamada [4], Takayuki Mima [1], and Takafumi Noguchi [5]

[1] Technical Research Institute, The Nippon Road Co., Ltd, Tokyo, Japan, [2] Haikou Onoda Remicon Inc. Shiga, Japan, [3] Hazama Ando Corporation, Tokyo, Japan, [4] Taisei Rotec Corporation, Tokyo, Japan, [5] Professor, The University of Tokyo, Tokyo, Japan
* Corresponding author; e-mail: hiroshi.fujii@nipponroad.co.jp

Abstract: The reduction of greenhouse gas emissions and atmospheric CO_2 is a critical global effort and actively researched across various fields. The authors have been trying to reduce embodied CO_2 in the pavement field by utilizing cement concrete wastages. Through previous studies, the technologies to fix CO_2 with aggregates by accelerating the carbonation or direct air capture of waste materials such as returned or leftover concrete and sludge in their fresh state were developed. This study aimed to produce CO_2-fixed aggregates (CFA) at a real-scale facility and implement CO_2-fixed pervious concrete pavement (CFPP) using these aggregates. Firstly, the CO_2 fixation amount in CFA was confirmed. The results showed that approximately 30 kg/ton of CO_2 was fixed in coarse aggregates and approximately 5 kg/ton in fine aggregates. Secondly, the relationship between air void and bending strength of CFPP using CFA was confirmed, and we set the target air void at 10%. The optimum water-to-binder ratio (W/B), a crucial factor for CO_2 fixation and pavement strength after construction, was found to be 35%. After confirming the method for controlling the air void of CFPP in actual plant facilities, a field trial was conducted in the 210 m^2 parking lot. The results showed that the durability and pavement surface performance met the required standards. An estimated 21% reduction in CO_2 emissions was achieved during the construction of the CFPP in the field trial, compared to conventional use of virgin aggregates. Including the accelerated carbonation process under consideration for early post-construction application, the total reduction is projected to reach 37%.

1. Introduction

The reduction of greenhouse gases, particularly CO_2 emissions, is a critical global challenge and the focus of extensive research across various fields. The pavement industry is no exception, with numerous studies continuously conducted to promote a sustainable society by balancing infrastructure development with environmental protection. In particular, considerable attention has been given to the use of plant-based binders as alternatives to petroleum asphalt, the incorporation of CO_2-absorbing materials, and the decarbonization of paving machinery and production processes in Japan. This trend is largely driven by the fact that approximately 90% of pavements in Japan are asphalt pavements, leading to hot mix asphalt becoming the dominant paving material (*MLIT 2025*). In contrast, cement concrete pavement is more commonly used overseas. Recently, the high durability of concrete pavement has been re-evaluated in Japan, and its wider adoption is expected to be encouraged through future government policies. Accordingly, technologies related to concrete materials and construction methods are actively being developed.

In the field of concrete pavement, the most of CO_2 emissions are generated from the production of cement clinker. Specifically, CO_2 is released through the decarbonation of limestone and the fuel consumption required during the calcination process. As a result, the CO_2 emission intensity of cement is higher than that of other materials (*Andrew 2019*). From this perspective, research in the cement sector is actively focused on replacing part of ordinary cement with low-CO_2 materials, such as sludge fine powder. Additionally, research has been conducted on CO_2 fixation during the curing process of concrete products by utilizing materials with high reactivity to CO_2 (*Taguchi 2024*).

Meanwhile, the authors have investigated an alternative approach through the Green Innovation Fund Program of the New Energy and Industrial Technology Development Organization (NEDO) (*Suzuki 2023*). According to Iwafuchi et al., waste from ready-mixed concrete, such as returned concrete, leftover concrete, and sludge, can be effective carbonated through accelerated carbonation or direct air capture (DAC) (*Iwafuchi 2024*). This process enables these concrete wastes to serve as raw materials for CO_2 fixation. This paper presents the results of a case study on the utilization of CFA, which were produced by granulating, sieving, and CO_2- fixing concrete waste developed by Iwafuchi et al. In particular, the results of laboratory tests and real-scale field trials are presented, focusing on CFPP made with coarse aggregate (CFC) and fine aggregate (CFF) derived from CFA. Finally, CO_2 emissions are estimated and compares with those of conventional pervious concrete made with virgin aggregates.

2. Objectives of Study

This study aims to assess the implementation and development of CO_2-fixed pervious concrete while estimating the reduction in CO_2 emissions. The authors focus on the structural characteristics of pervious concrete pavement (PP). This is because PP contains many macro air voids, which allow rainwater and CO_2 to permeate into the pavement structure. As a result, active calcium sites, such as calcium hydrate, are expected to undergo carbonation reactions and effectively fix CO_2.

3. Materials Information

3.1 Carbon Fixed Aggregate

This study focuses on the production of granulated recycled aggregates (GRA) derived from simulated returned concrete. The concrete used in the simulation had a compressive strength 24 N/mm^2, slump of 12 cm, maximum aggregate size of 20 mm, and was composed of ordinary Portland cement. The concrete was prepared at an actual plant, where a granulating additive was incorporated after simulating transportation. The resulting GRA was cured overnight, crushed the following day, and stored into size categories: 15-5 mm and 5-0 mm. Subsequently, the GRA underwent a specified carbonation treatment. **Photo 1** shows the granulation process.

Photo 1 GRA production process: a) Granulating, b) Crushing, c) Sieving

3.1.1 Coarse Aggregate

The coarse aggregate of GRA (GRC) was classified into the 15-5 mm size range and carbonated in an accelerated carbonation facility. **Figure 1** shows an image of this facility. This system circulates CO_2 gas, which is supplied from external tanks and directed from the bottom to the top of the GRC chamber, then into the dehumidifying chamber before being recirculated back into the GRC chamber.

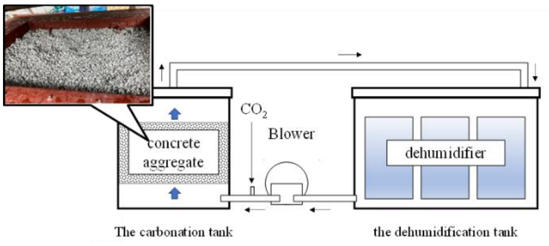

Fig. 1 Image of accelerated carbonation facility

3.1.2 Fine Aggregate

The fine aggregate of GRA (GRF) was sorted into the 5-0 mm size range and naturally carbonated through direct air capture (DAC) for seven days, during which it was intermittently mixed with a backhoe.

3.2 Pervious Concrete

The performance of CFPP was evaluated in comparison to PP using virgin aggregates. In this study, utilized normal Portland cement. Additionally, an inorganic additive, applied at a dosage of 15 kg/m^3 of concrete, was incorporated to enhance strength and reduce excessive sagging of the cement paste. Furthermore, due to the extremely low W/B, a set-retarding additive was incorporated at a dosage of 0.3% of the cement weight to ensure the concrete maintained its workability.

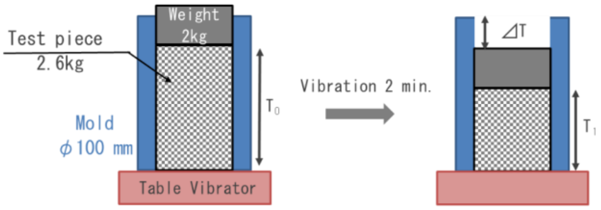

Fig. 2 Test concept of settlement method

4. Test Methods

4.1 Mix Design of Pervious Concrete

The air void ratio and cement paste consistency were controlled by adjusting key factors, such as the mortar-void of coarse aggregate ratio (*Km*) and the paste-void of fine aggregate (*Kp*), based on the method reported by Kajio (*Kajio et., al. 2008*). The material proportions of the mixture were determined using this method, followed by trial production. The air void ratio of the mixed concrete was assessed using the settlement method for porosity. **Figure 2** showed the test method concept. Specifically, a fixed quantity of concrete was placed into a cylindrical mold, a weight was applied to the top of the test specimen, and excitation was conducted for 2 minutes. The settlement amount was measured to determine the air void ratio under a fully compacted state. This method is applicable for assessing concrete quality both during shipment and arrival at the construction site, as it is suited for fresh state concrete.

4.2 Bending Strength

The strength of CFPP was evaluated using a bending strength test. Based on Japanese standards, concrete pavement typically requires a bending strength of 4.4 MPa at 28 days of aging. However, for parking lot applications, the required bending strength is lower, at 3.5 MPa. Consequently, the target bending strength for CFPP in this study was set to 3.5 MPa.

4.3 Water Permeability

The CO_2 fixation function associated with the water permeability of PP was anticipated. Accordingly, the amount of permeable water was evaluated as one of the functional aspects of CFPP. This test method followed the standard method S025 outlined in the Japanese handbook (*Japan Road Association 2019*). The procedure consisted of measuring the flow rate of 400 mL of water poured into a cylindrical mold and converting the data to estimate the volume of water that passed through within 15 seconds.

5. Test Results and Considerations

5.1 CO_2 Fixation of Aggregates

The experiment on CO_2 fixation using GRA was conducted by carbonating GRC and GRF for 3 and 7 days, respectively. The amount of CO_2 fixation was evaluated through wet analysis, a total organic carbon analyzer, and thermogravimetric-differential thermal analysis (TG-DTA). In this study, we provisionally adopted the results obtained from TG-DTA. Specifically, the weight reduction observed between 550 °C and 850 °C, corresponding to the decarbonation reaction of calcium carbonate, was measured.

5.1.1 Properties of Course Aggregate

Table 1 presents the aggregate properties of GRC and CFC. Both GRC and CFC exhibited significantly higher water absorption compared to virgin aggregates. This is attributed to the influence of hardened mortar adhering to the raw material aggregates. Additionally, the solid content was higher for GRC and CFC, which is likely associated with their rounded, fully-filled shapes in comparison to the irregular shape of virgin aggregates. Furthermore, the amount of CO_2 fixed by CFC was approximately 30 kg/ton.

Table 1 Properties of GRC and CFC

Indicator		GRC	CFC
Density	(g/cm^3)	2.47	2.49
Water adosorption	(%)	5.5	4.6
Solid content	(%)	57.1	67.3
CO_2 fixation	(kg/ton)	N/A	30.05

Table 2 Properties of GRF and CFF

Indicator		GRF	CFF
Density	(g/cm^3)	2.33	2.27
Water adosorption	(%)	10.1	12.2
Solid content	(%)	67.3	57.1
CO_2 fixation	(kg/ton)	N/A	5.12

5.1.2 Properties of Fine Aggregate

Table 2 presents the aggregate properties of GRF and CFF. Both GRF and CFF exhibited significantly higher water absorption and slightly lower density compared to virgin aggregates. These results are attributed to the high content of cement fine particulates generated during their production process. The CO_2 fixation by CFF was approximately 5 kg/ton. However, based on the results of Section 5.1.1, it is expected that CO_2 fixation can be further increased and accelerated by improving and developing the carbonate acceleration method for GRF.

5.2 Mix Design of Pervious Concrete

The properties of CFPP were confirmed through mix design tests conducted in the laboratory after gaining a thorough understanding of the characteristics of GRA and CFA. Based on these results, real-scale production tests were carried out at an actual plant to verify the selected optimum mixture design.

5.2.1 Laboratory Test

5.2.1.1 *Km*, Air Void, and Bending Strength

Firstly, CFA was considered weaker than raw aggregates due to the presence of hardened mortar attached to the raw material aggregates. Consequently, the air void ratio become the primary factor influencing the strength of pervious concrete pavement. Based on this, an investigation was conducted to regulate the air void ratio by using *Km* as the primary factor in the mix design for PP prepared with GRA. **Figure 3** shows the test results, confirming a high correlation between *Km* and air void. However, variations in aggregate quality led to differences in the degree of influence within a similar *Km* range. These results indicate that the use of *Km* enables control over the air void ratio in PP. Then, specimens with air void ratios ranging from 4% to 20% were prepared to investigate the effect of air void ratio on bending strength. **Figure 4** presents the test results, including reference data for virgin aggregate for comparative analysis. The bending strength of PP using GRA decreased as the air void ratio of the specimens increased. In this study, the design bending strength was set at 3.5 MPa, in accordance with the requirements for standard parking lots. Therefore, the target air void ratio was determined to be 10%, as this condition is expected to achieve a bending strength of 4.6 MPa, including the additional strength calculated as follow.

$$f_{br} = (f_{bk} + f_p) \times p \qquad (1)$$

Where f_{br}: Target strength, f_{bk}: Design strength (3.5MPa), f_p: Additional strength (0.8), p: Overdesign factor as coefficient of variation is 10% (1.09)

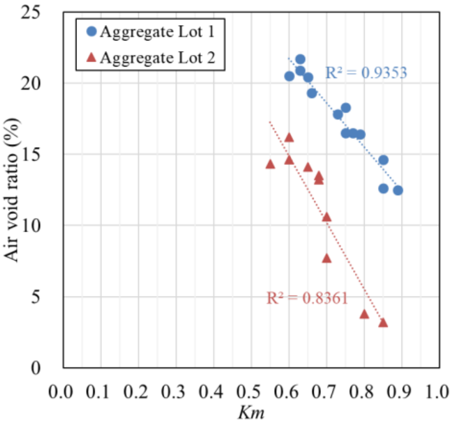

Fig. 3 Effect of *Km* on air void ratio

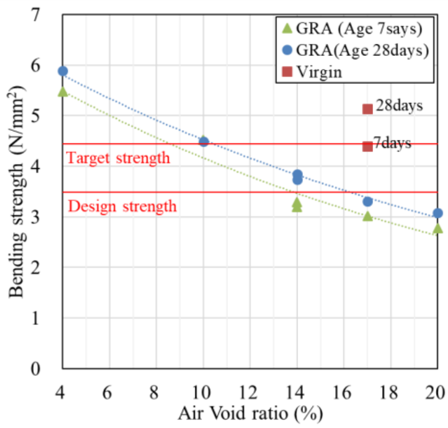

Fig. 4 Effect of air void ratio on bending strength

5.2.1.2 Water-to-Binder

Based on the above, the effect of W/B, ranging from 21% to 45%, on bending strength was investigated while maintaining a fixed specimen air void ratio at 10%. The results are shown in **Figure 5**. From these results, bending strength showed a gradual decrease as W/B increased at both 7 and 28 days of aging. Therefore, the optimum W/B was determined to be 35% to ensuring the target strength.

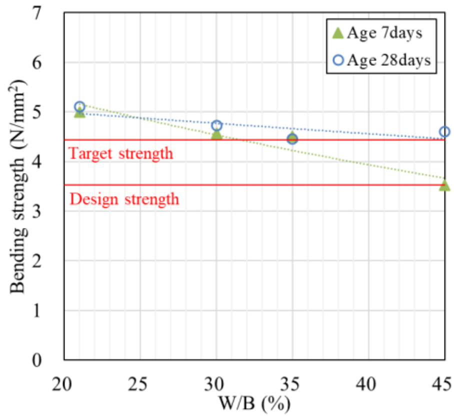

Fig. 5 Effect of W/B on bending strength

5.2.1.3 W/B and Carbonation

W/B is considered to affect the amount of CO_2 fixation after construction. Therefore, pellet specimens composed solely of paste with varying W/B ratios were prepared and subjected to accelerated carbonation in cure chamber. The amount of calcium carbonate was then analyzed using TG-DTA. The conditions for accelerated carbonation were set as follows: a temperature of 30ºC, a humidity of 80%, and a CO_2 concentration of 80%. **Figure 6** shows the results. The amount of calcium carbonate increased with material age, and this trend became more pronounced as the W/B ratio increased. Based on these results, setting the W/B at 30 to 40% is expected to facilitate long-term CO_2 fixation after construction, with an estimated amount of approximately 125 kg per ton of paste.

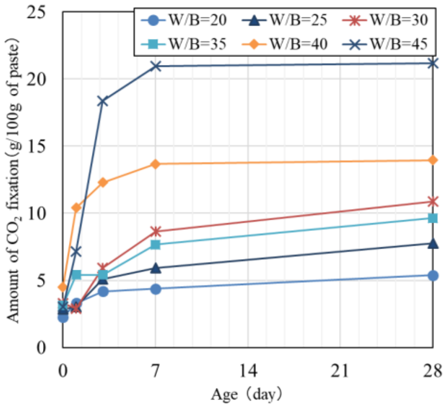

Fig. 6 Amount of CO_2 with accelerated

5.2.2 Actual Plant Test

Based on the relationship between air void, W/B, and bending strength, a real-scale production test was conducted at an actual plant. The air void ratio of the produced concrete was measured immediately after production and again after standing for 30 minutes. **Figure 7** presents the air void measurement results. Drawing from these results, air void ratio can be controlled by adjusting *Km*, similar to the laboratory test. In this study, the transportation time for concrete was assumed to be approximately 30 minutes during the field test. Consequently, *Km* was set at 0.78 as the specified mix factor, based on air void measurements obtained using the settlement method.

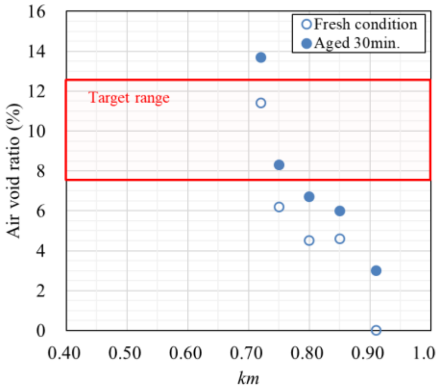

Fig. 7 Air void of the concrete produced by actual plant

Table 3 Mix proportions of CFPP and VPP

Mixture	Quantity of material per unit volume of concrete (kg/m³)					*Km*
	W	C	S	G	Ad	
CFPP	278	103	311	1429	15	0.78
VPP	272	101	409	1487	15	0.84

5.3 Field Trial

5.3.1 Fresh Condition and Construction

Table 3 shows the mix proportions for CFPP and pervious concrete using virgin aggregate (VPP). Air void ratio was measured both at the time of shipping and upon arrival at the site as part of the concrete quality test. **Figure 8** illustrates the results. From these results, both CFPP and VPP were confirmed to be suitable within the target air void range. The field trial was conducted over an area of approximately 210 m^2 with a thickness of 150mm using a wheeled asphalt paver. **Photo 2** provide examples of the construction

Photo 2 Construction process and surface condition: a) Paving, b) CFPP, c) VPP

process and surface conditions. The construction proceeded smoothly without any issues, thanks to the use of an asphalt paver, a custom rubber-coated roller, and a power trowel. The surface was in good condition, effectively forming the air void structure and framework without clogging.

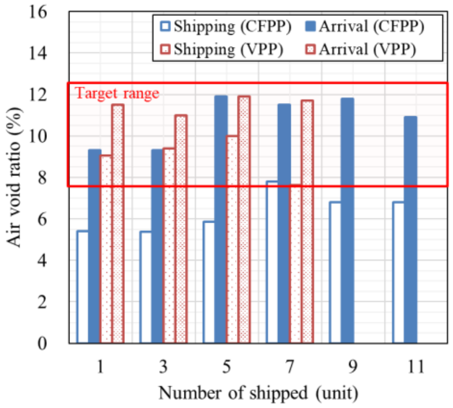

Fig. 8 Air void at shipping and arrival at the site

5.3.2 Bending Strength

Using specimens made from the concrete shipped to the site, bending strength tests were conducted at 7 and 28 days of age. From the data in **Table 4**, both CFPP and VPP met the target strength. The strength of CFPP remained unchanged between 7 and 28 days, whereas VPP exhibited approximately a 30% increase in strength. This outcome is attributed to the material composition – VPP consists of virgin aggregates, whereas CFPP is composed of recycled aggregates with hardened mortar adhering to the raw aggregates. In other words, the paste strength eventually surpasses the hardened mortar strength, making the hardened mortar the weakest point in the concrete and thereby limiting further strength development.

Table 4 Bending strength of CFPP and VPP specimens

Mixture	Bending strength (N/mm^2)		
	7 days	28 days	Design
CFPP	4.6	4.4	3.5 or more
VPP	5.0	6.5	

5.3.3 Pavement Properties

Table 5 shows the results of performance measurements conducted 7 days after construction. The finding indicates that both CFPP and VPP exhibited comparable values in skid resistance, dynamic friction, water permeability, and texture depth, all of which met the required standards.

Table 5 Pavement properties of CFPP and VPP

Mixture	Indicator			
	Skid resistance (BPN)	Dynamic friction (μ60)	Water permeability (ml/15s)	Texture depth (mm)
CFPP	88	0.38	1,100	1.5
VPP	85	0.36	1,300	1.3

5.4 Estimation of CO₂ reduction

CO_2 emissions associated with the production phase of PP were estimated using field trial materials and the specified mixture design. The results are presented in **Figure 9**. For this estimation, the CO_2 emission intensity of CFA, measured and calculated in Sections 5.1.1 and 5.1.2 was utilized. Additionally, the CO_2 emission intensities of other materials were referenced according to the Japan Concrete Institute. The result shows that CFPP reduces CO_2 emissions by 21% compared to VPP during construction, equivalent to 1,600 kg of CO_2 based on the adopted volume. Furthermore, based on the results presented in section 5.2.1.3, and taking into account the accelerated carbonation process currently under consideration, the CFPP is expected to achieve a total CO_2 reduction effect of 37%, equivalent to approximately 2,790 kg, when including CO_2 fixation after construction.

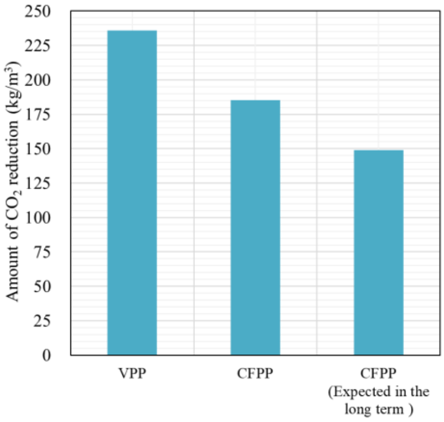

Fig. 9 Estimation results of CO_2 reduction effect

6. Summary and Conclusion

This paper is summarized as follows.

- The air void ratio of CFPP can be controlled by adjusting *Km* as a parameter of the mix design.
- The strength of CFPP is predominantly influenced by air voids, and its final strength may depend on the hardened mortar attached to the original aggregates.
- CFPP meets the required performance standards for pavement applications and is suitable for parking lots with a design strength criterion of 3.5 MPa.
- CFPP achieves a 21% reduction in CO_2 emissions compared to VPP, with the potential to reach 37% over the long term through CO_2 fixation during its service life.

This research was conducted as part of a commissioned project (JPNP21023) by the New Energy and Industrial Technology Development Organization (NEDO). We sincerely appreciate the support and contributions of all those involve.

References

Ministry of Land, Infrastructure, Transport and Tourism (MLIT). (2025). Road Design Standards. Retrieved from (https://www.mlit.go.jp/sogoseisaku/inter/keizai/gijyutu/pdf/road_design_j2.pdf), Japan. (in Japanese)

Andrew, R. M. (2019). Global CO_2 Emissions from Cement Production, 1928-2018. Earth Science Data. Retrieved from (https://essd.copernicus.org/articles/11/1675/2019/)

Suzuki Y., Noguchi T., Saito T., Sakamoto M., Shiraiwa S. (2023). Development and Implementation of Carbon Pool Concrete for Both Resource Recycling and Carbon Neutral, 77th RILEM Annual week & 1st Interdisciplinary Symposium on Smart & Sustainable Infrastructures RILEM week 2023, Canada

Iwafuchi T., Suzuki Y., Yamauchi K. (2024). CO_2 Fixed by Recycled aggregate in a Medium-Scale Carbonation Facility, Conference Proceedings of ReACT2024, vol.1, pp.83-84

Kajio S. (2008). Study on Mix Design and Void Characteristics of Porous Concrete. Doctoral Dissertation, Tokyo Metropolitan University, Japan (in Japanese with the English abstract)

Japan Road Association. (2019). The handbook of pavement investigation and test methods.