C^4S Research & Development Project

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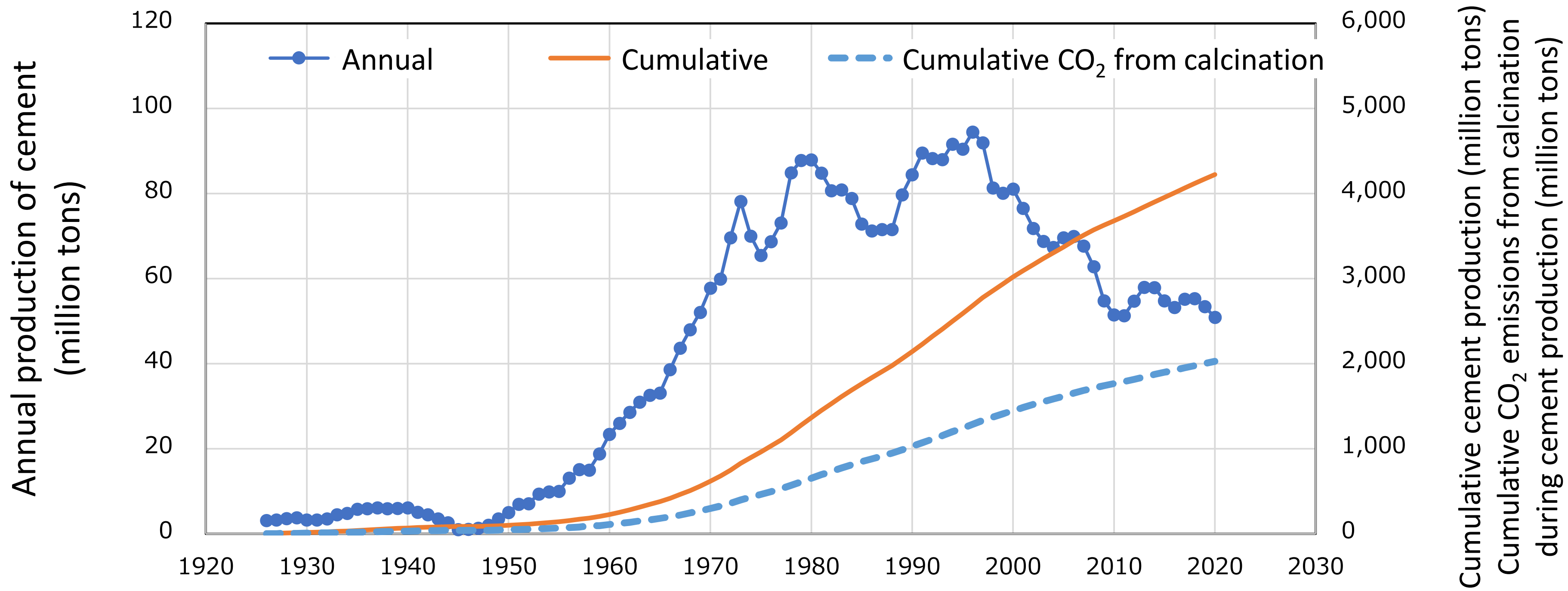
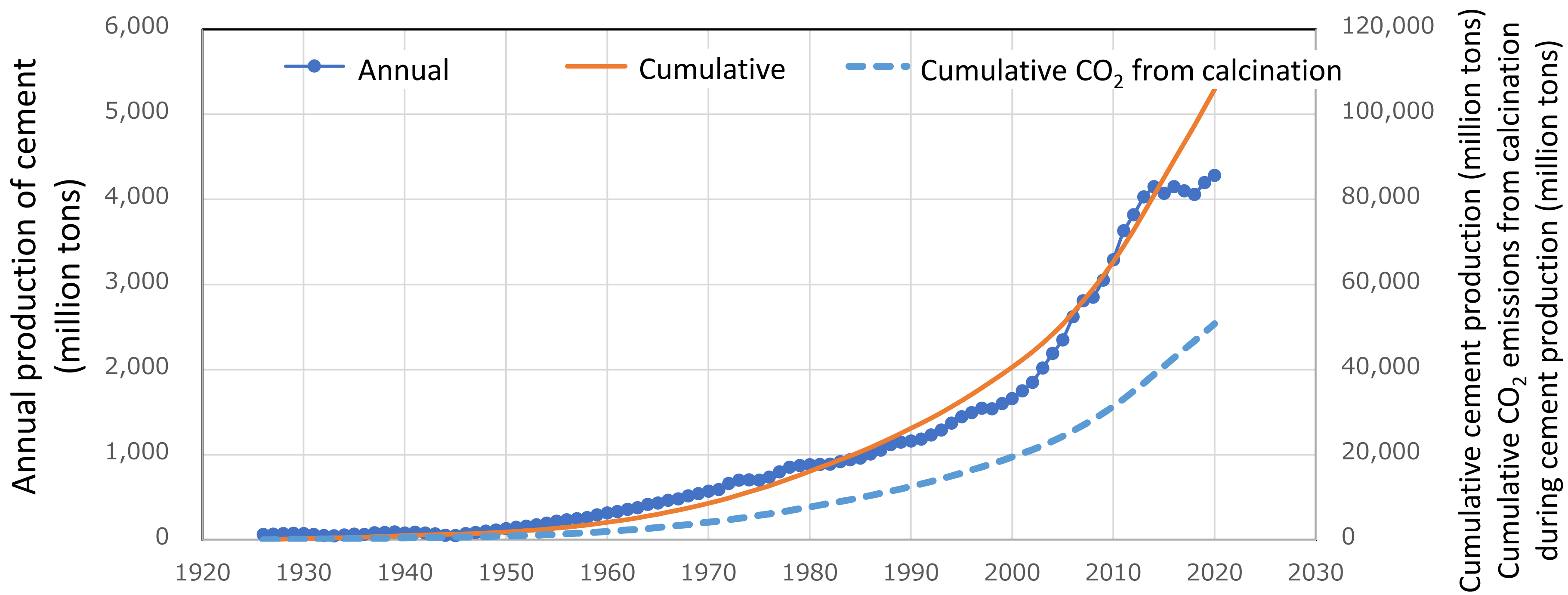
The University of Tokyo, Professor
PJ participating organizations:
The University of Tokyo
Hokkaido University
Recommissioned organizations:
Tokyo University of Science
Kogakuin University
Utsunomiya University
Shimizu Corporation
Taiheiyo Cement
Masuo Recycle

Background (Cement production & CO_2), Objective

Japan



World



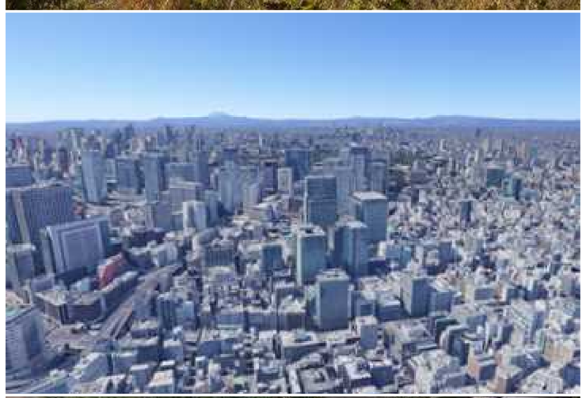
■ **Total CO_2 in air**
2.8 trillion tons

■ **CO_2 emission from calcination during cement production**

- Cumulative
  - World **55 billion tons**
  - Japan **2 billion tons**
- Annual
  - World **2.1 billion tons**
  - Japan **26 million tons**

Capture & Utilization (CCUS) by Concrete

Background, Method for CCUS



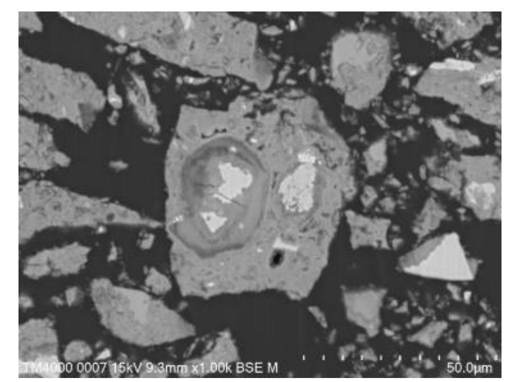
Extraction of **limestone ($CaCO_3$)** to produce cement, etc.

→ Always generate CO_2 when using calcium (**Ca**)

Concrete, which is no longer used around the world, is a valuable source of calcium (**Ca**) (Reacting with CO_2 to form carbonate)

Crushing waste concrete

Binding CO_2 in the air



$CaCO_3$ formation

CCC

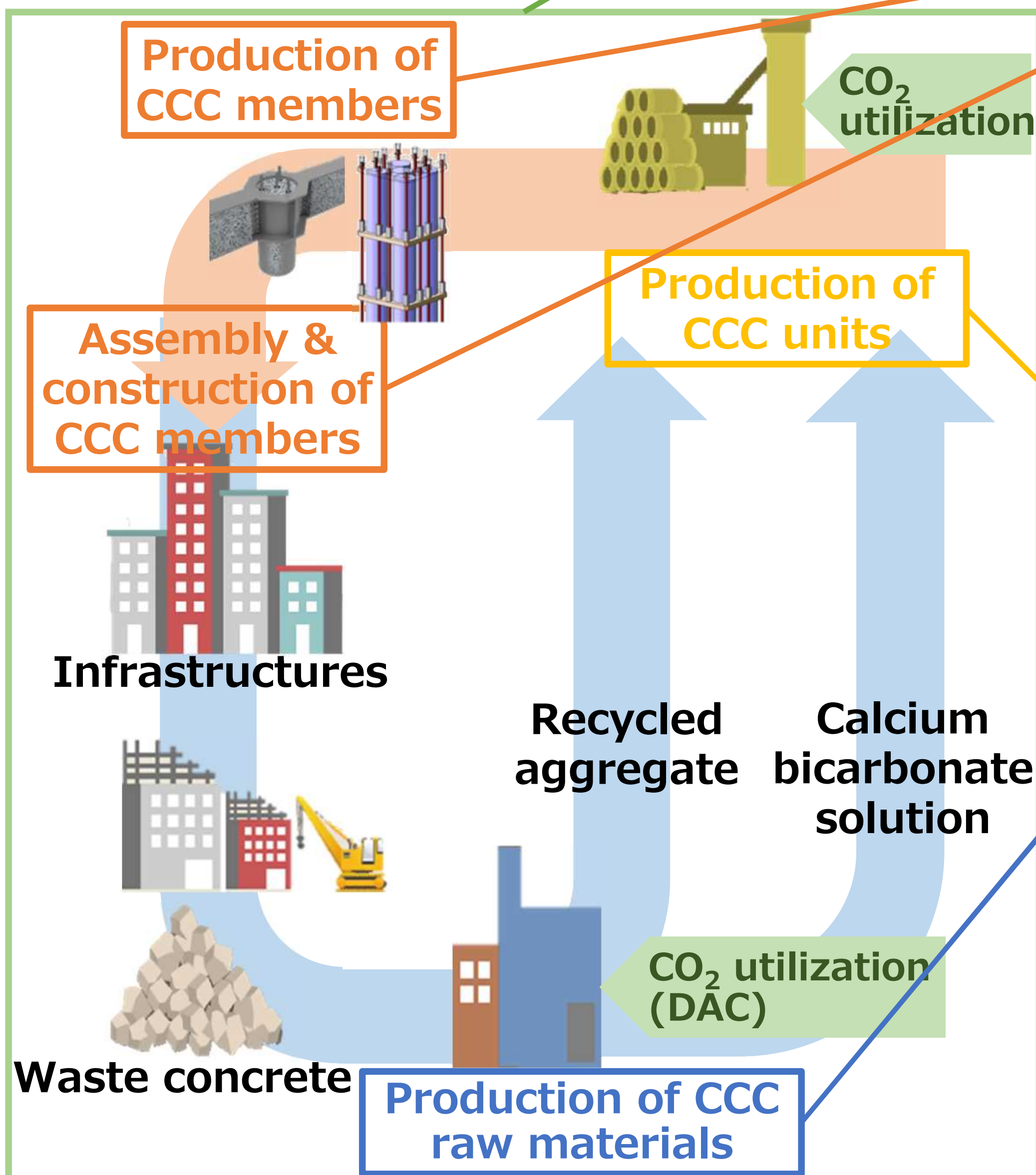
Produce **calcium carbonate concrete** (**CCC**) to **capture and fix CO_2** in the air released by calcination of limestone during cement production **with Ca**, and permanently circulate CO_2 and Ca

Overall Picture of C⁴S R&D Project

Target: Amount of DAC in 2050 in case of C⁴S realization (50% of concrete is CCC)

Japan: ▲13 million tons-CO_2/year

World: ▲1 billion tons-CO_2/year



Social implementation (PJ III)

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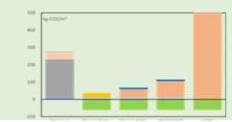
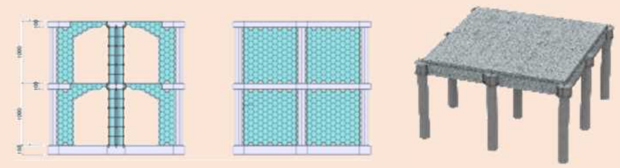
- Institutional design related to building codes
- Design of resource recycling scenarios
- CO_2 emission reduction/fixation effectiveness analysis



Manufacturing principles for CCC components (PJ I)

Structural design for CCC structures (PJ III)

- CCC members: manufacturing, structural form, performance evaluation
- CCC structures: structural design and construction



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CCC reaction control (PJ I)

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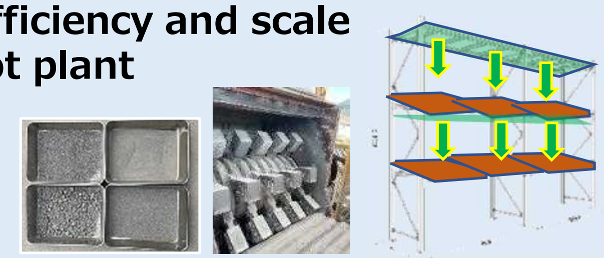
- CCC unit: reaction mechanism, formulation design, manufacturing and quality control, performance evaluation
- CCC unit manufacturing plant: pilot design

CCC raw material manufacturing process (PJ II)

- Crushing of waste concrete and fixation of CO_2 absorption
  - Improvement of efficiency and scale
  - Deployment to pilot plant



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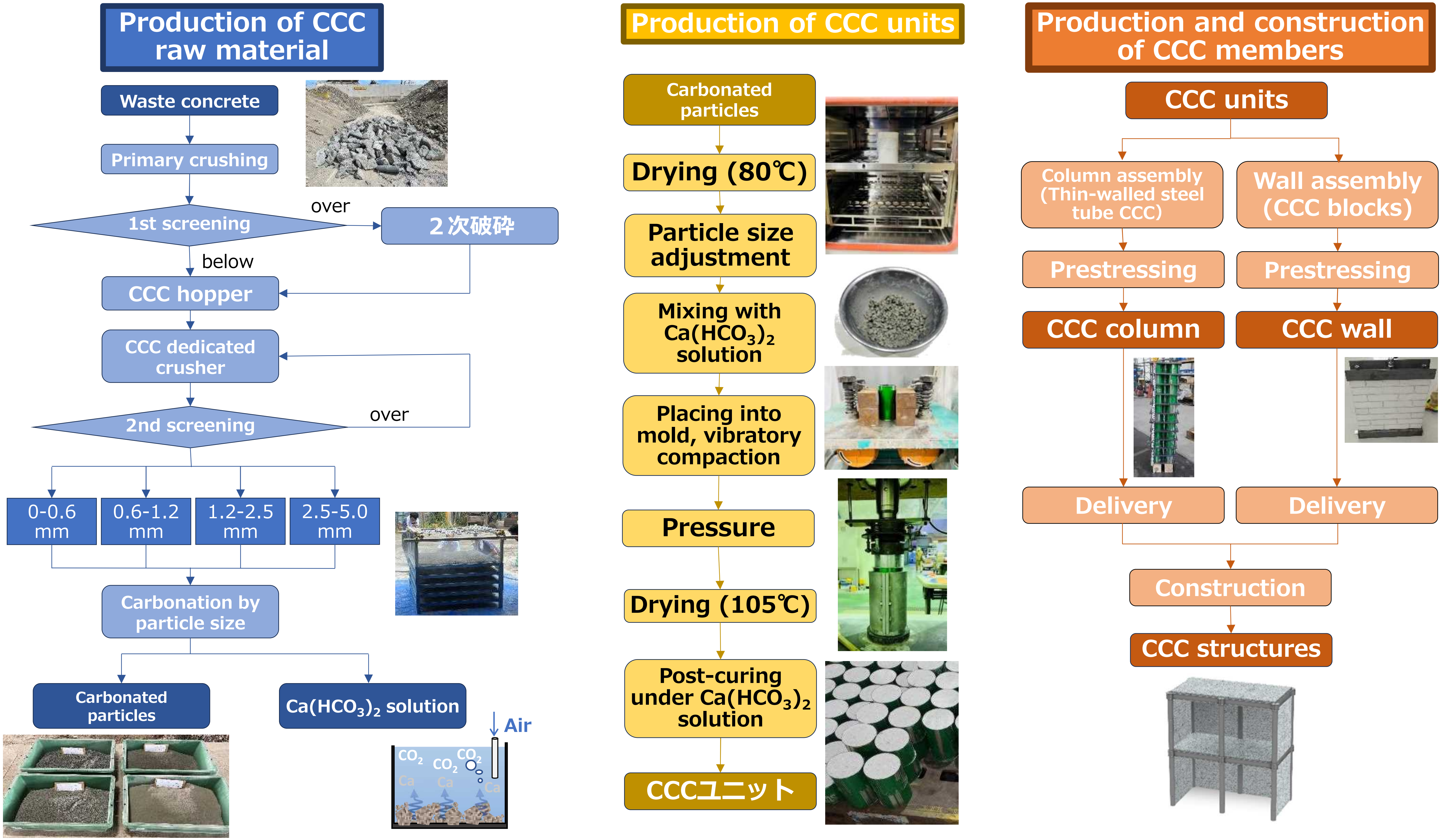
Masuo Recycle

Development Schedule, Targets

R&D items	Target at the end of FY2023	Target at the end of FY2024 (Interim)	Target at the end of FY2029 (Final)
KPI	■φ15x30cm specimen with stable **strength of 20MPa** ■Started manufacturing **column and beam** at bench plant	■**30MPa strength** in specimens ■**12MPa strength** in column ■Production of column and beam at bench plant ■Construction of **mockup structures**	■**30MPa strength** in column ■Started supplying earthquake-resistant and durable **low-rise buildings**
①PJ I **Development of CCC reaction control technology and component manufacturing principles**	■Fabrication of **bench plant** ➢φ0.15x0.3m column unit ➢0.2x0.1x1m beam ■Clarification of **manufacturing principles** for components with stable quality and performance	■**Member manufacturing** at bench plant ➢120 column units/month ➢42 beam units/month ■Construction of **mockup structures** ➢W×D×H=2×1×3m 2-layer structure	■**Manufacturing components** in **pilot plant** ➢250 φ0.3x0.6m pillar units/month ➢120 0.4x0.2x2m beam units/month ■**Building** construction ➢2 stories
②PJ II **Development of manufacturing processes for CCC raw materials**	■Fabrication of bench plant ■Determination of efficient **raw material production process** ■Determination of efficient **CO_2 capture process**	■**Raw material production** at bench plant ➢5 tons/month ■**CO_2 capture** ➢2960 kg/year	■**Raw material production** at **pilot plant** ➢90 tons/month ■**CO_2 capture** ➢54 tons/year
③PJ III **Development of structural design and performance evaluation methods for CCC structures and social implementation of C⁴S**	■Collection of **structural design data** ■Clarification of data required for **Minister of Construction approval**, etc. ■Prediction of **waste concrete** emissions based on regional characteristics ■Identification of **CO_2 emission and absorption balance** at bench plant	■Establishing outline of **structural design method** ■Clarification of procedures and collection of necessary materials for obtaining **Minister of Construction approval**, etc. ■Presentation of the direction of optimal **resource circulation scenario** ■Presentation of measures for **minimizing CO_2 emissions and maximizing absorption**	■Establishment of **methods for structural design and durability design** ■Obtaining **Minister of Construction approval** for **structural methods** ■Proposal of **revisions to technical standards regarding building materials** ■Completion of optimal **resource circulation scenario** ■Confirmation of **C⁴S validity** based on LCA evaluation

CCC Structure Construction Procedures



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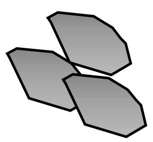
Development of Manufacturing Processes for CCC Raw Materials

Methods for CO_2 Capture Acceleration

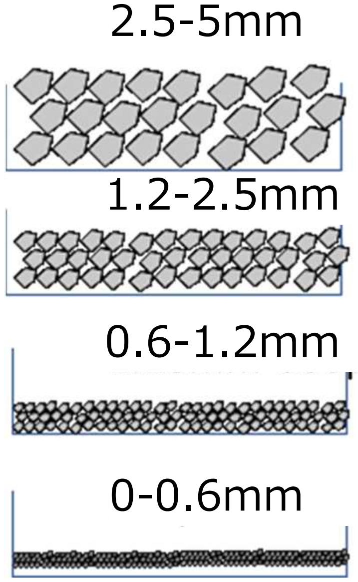
Granulation

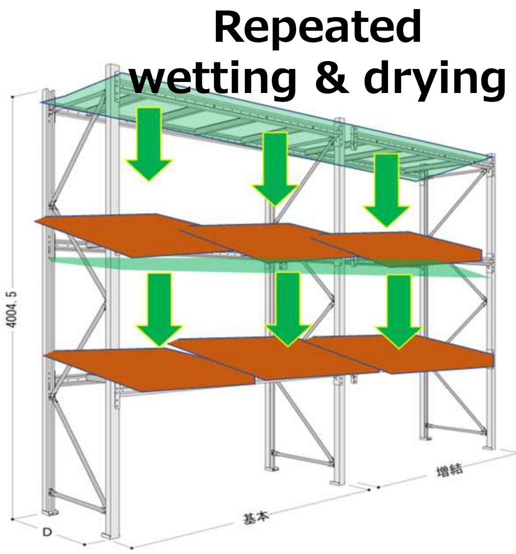
Crushing and **classification** of waste concrete → **Single particle size** → Securing of **aeration channels** → **Acceleration of carbonation** by dry/wet repetition for each particle size → **Enhancement of DAC**



Human head-sized waste concrete

Classification

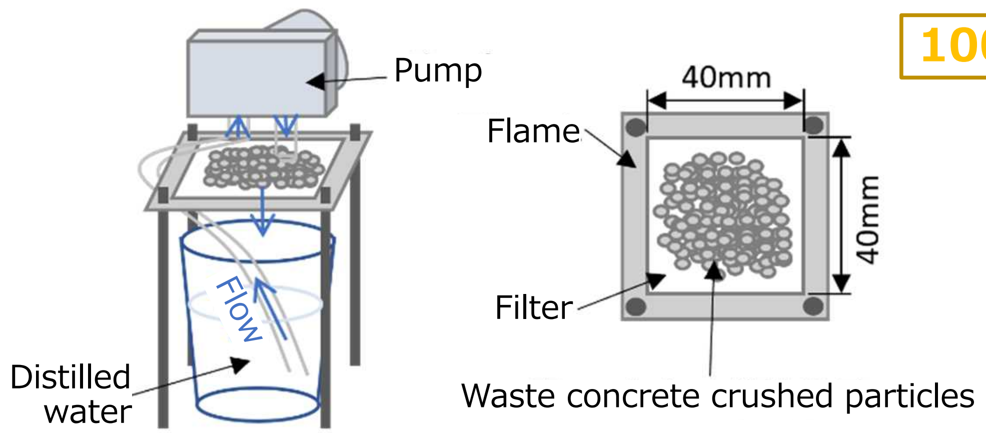




- **Acceleration of carbonation**
  $CaO + CO_2 \rightarrow CaCO_3$
- **Enhancement of DAC**

Methods for CO_2 Capture Acceleration

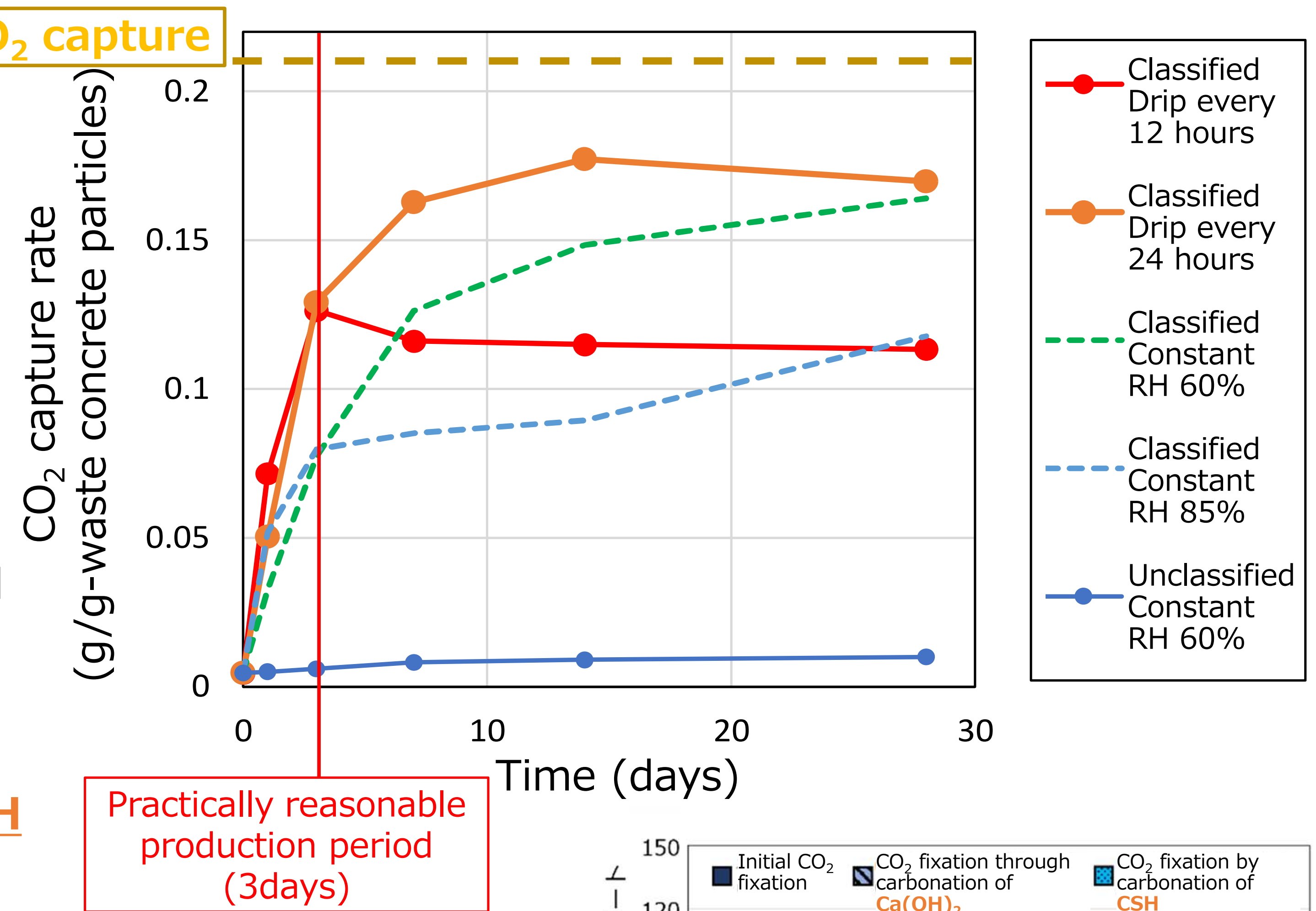
Drip method



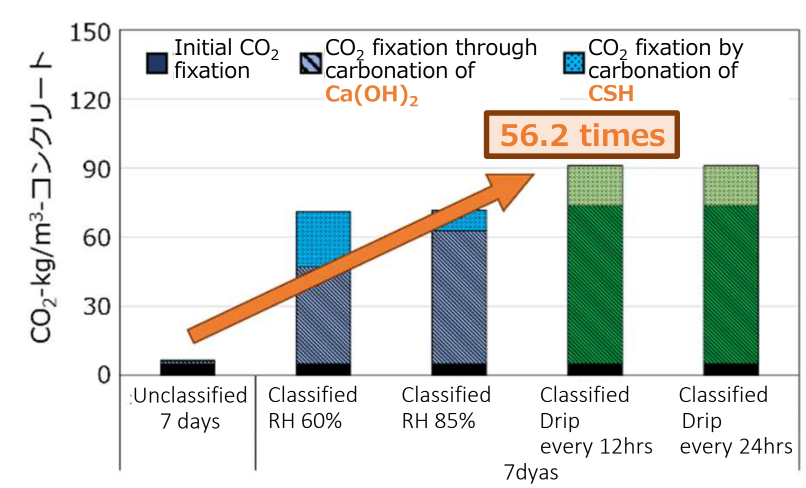
Dripping water periodically on
8.238ml every 12 hours
every 24 hours
crushed waste concrete particles for 15 second
1.677g

Repeated wetting & drying

Carbonation of $Ca(OH)_2$
Accelerated carbonation of CSH



Drip method
the most practically **advantageous** method for **carbonation** by **DAC**



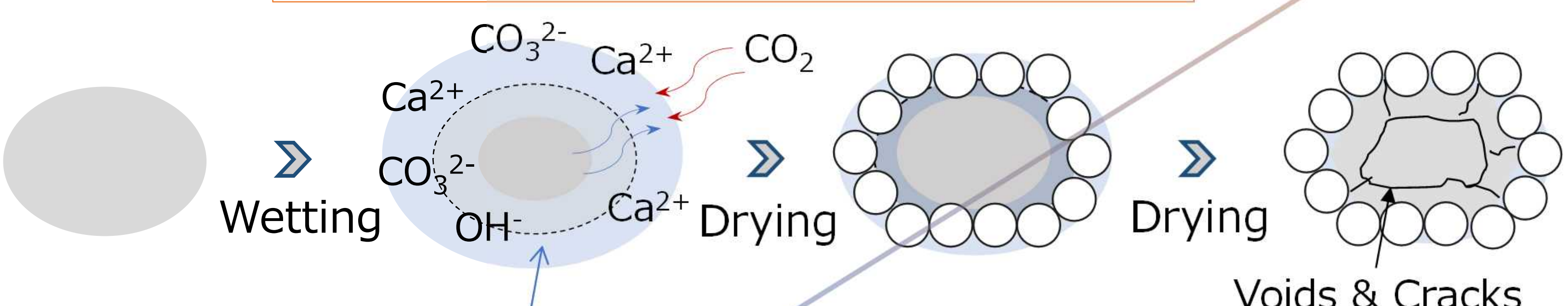
Methods for CO_2 Capture Acceleration

Dripping water

Easy to manage and extremely fast, but particles being more fragile

Water / Waste concrete particles / $CaCO_3$

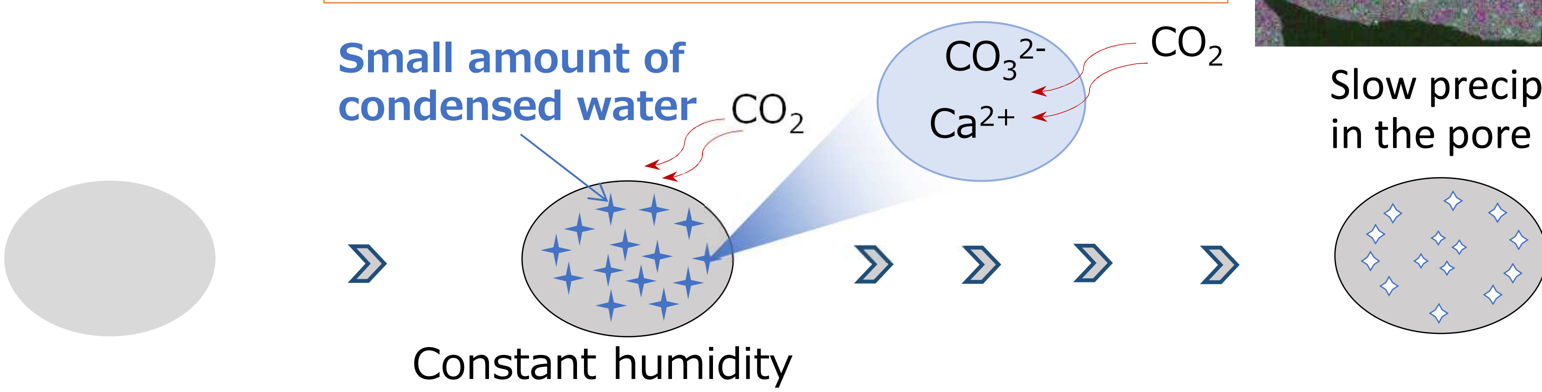
CO_2 fixation reaction field: surface + outside

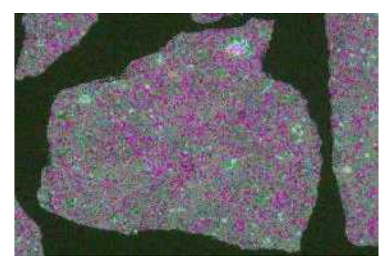


Constant humidity

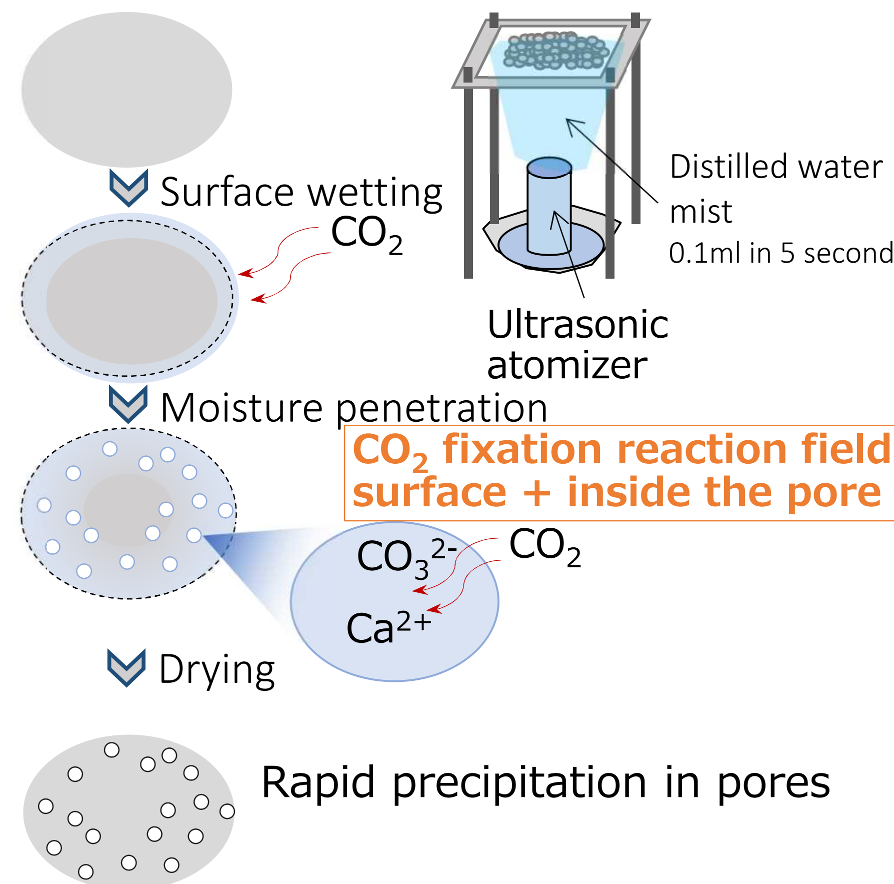
Difficult to control, slow speed, but high particle density

CO_2 fixation reaction field: inside the pore





Mist supply



Easy to manage
Aiming to promote CO_2 fixation through surface and internal reactions by spraying a small amount of mist

Toward the Installation of a Pilot Plant

- Improving the accuracy of operations on a small site
- Planning of actual installation, including flow line images
- Introduction of grab forks (plant maintenance and operational testing)
- Improving efficiency of manual operation methods
- Addition of carbonation accelerators such as misting equipment

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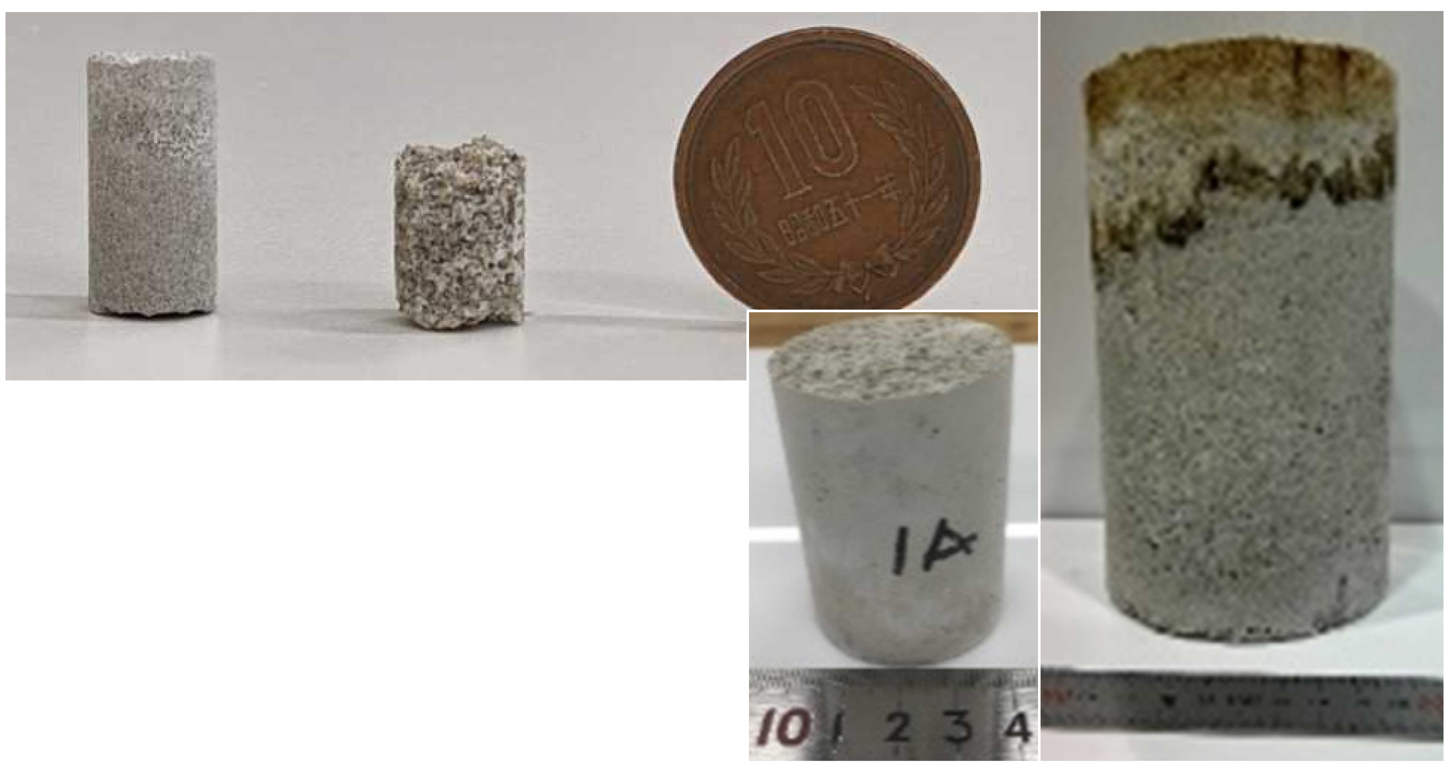
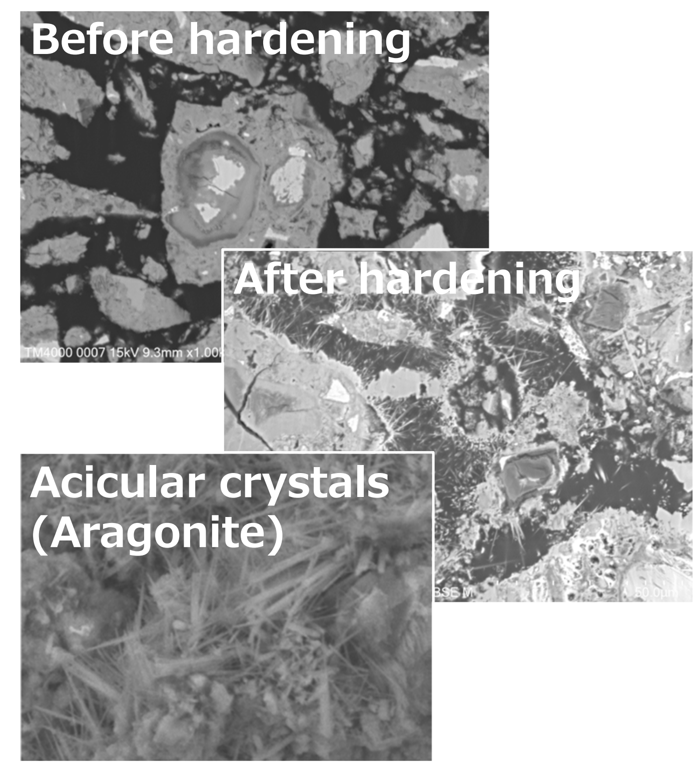
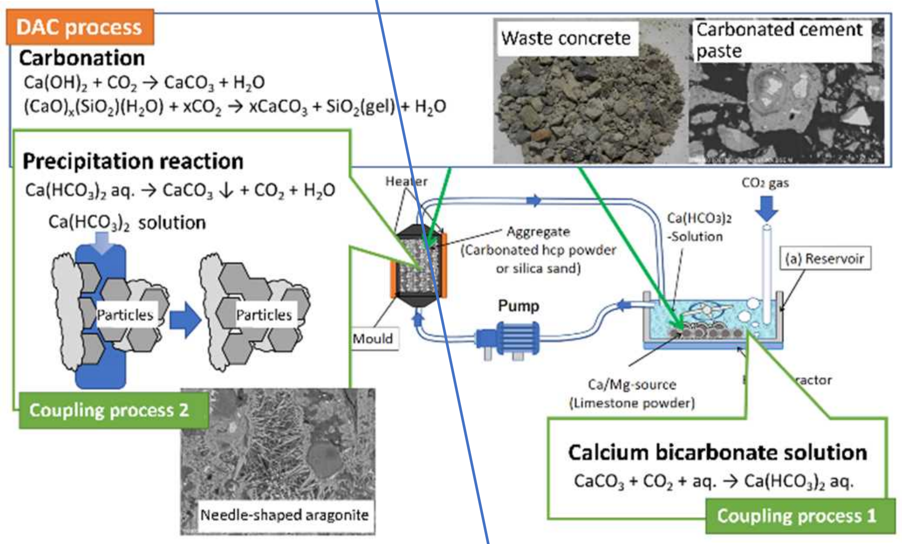
Development of CCC Reaction Control & Stabilized Manufacturing Technologies



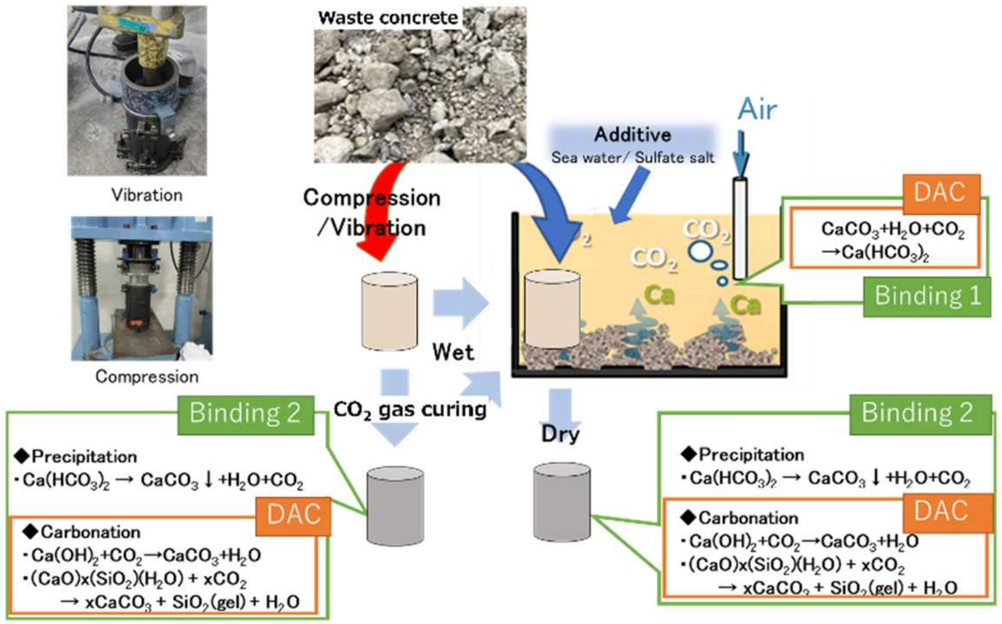


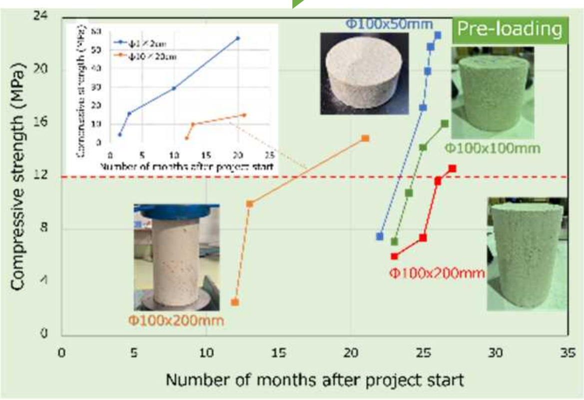
Various Manufacturing Methods for CCC

Precipitation method

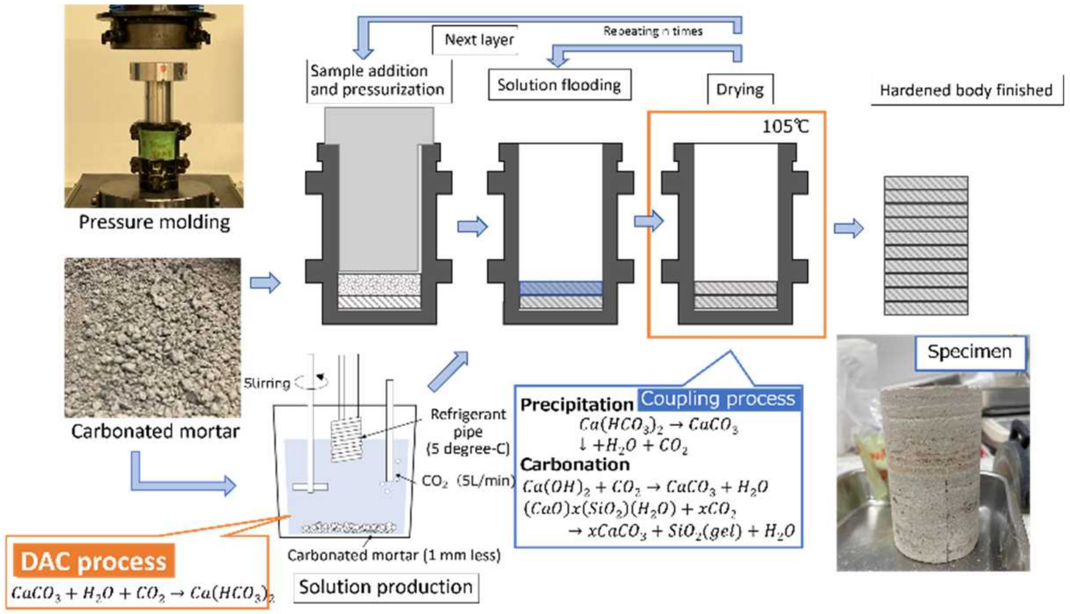


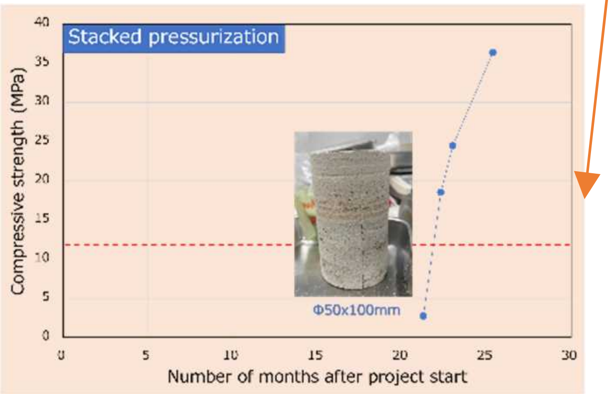
Pressurization method





Stacked pressurization method





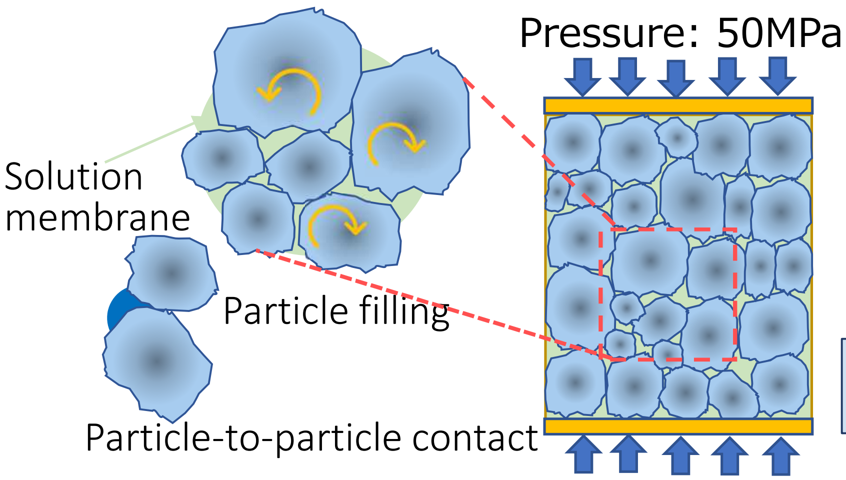
Issues for Social Implementation

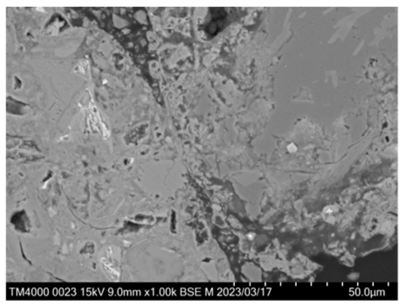
- Larger size and higher strength
- Reduction of energy consumption
- Improvement of productivity

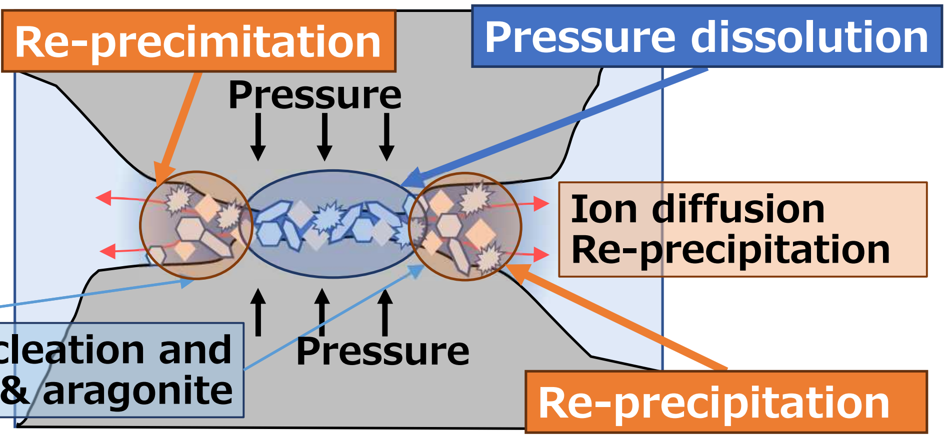
Cold Sintering Method

Mechanism of strength development

Initial pressurization
➡ Increase of actual volume ratio by particle filling
➡ Increase of contact area between particles
Long-term pressurization
➡ Increases of bonding surface and strength by pressure-solution



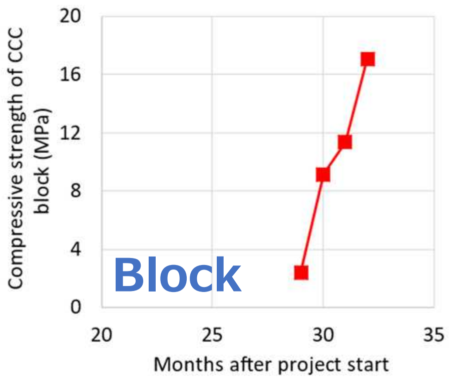


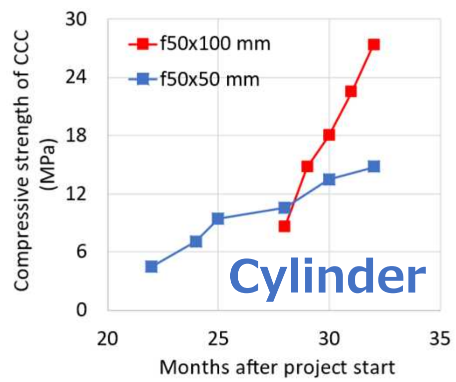


■ Optimization of Particle size distribution	➢ Reduction of CCC porosity ➢ Increase in aggregate-to-aggregate contact area ➢ Strengthening of CCC skeleton after pressure molding	Increase of compressive strength
■ Drying of CCC after pressure compaction	➢ Precipitation of $CaCO_3$ at the aggregate interface	Densification Bonding of aggregate particles
■ Immersion in $Ca(HCO_3)_2$ solution and drying (secondary curing)	➢ $Ca(HCO_3)_2 \rightarrow CaCO_3 + CO_2 + H_2O$ ➢ Further precipitation of $CaCO_3$ ➢ Further carbonation of uncarbonated portions by the resulting CO_2	Increase of compressive strength Large energy consumption

Higher strength

Currently, 20MPa in φ100x200mm size without any problems

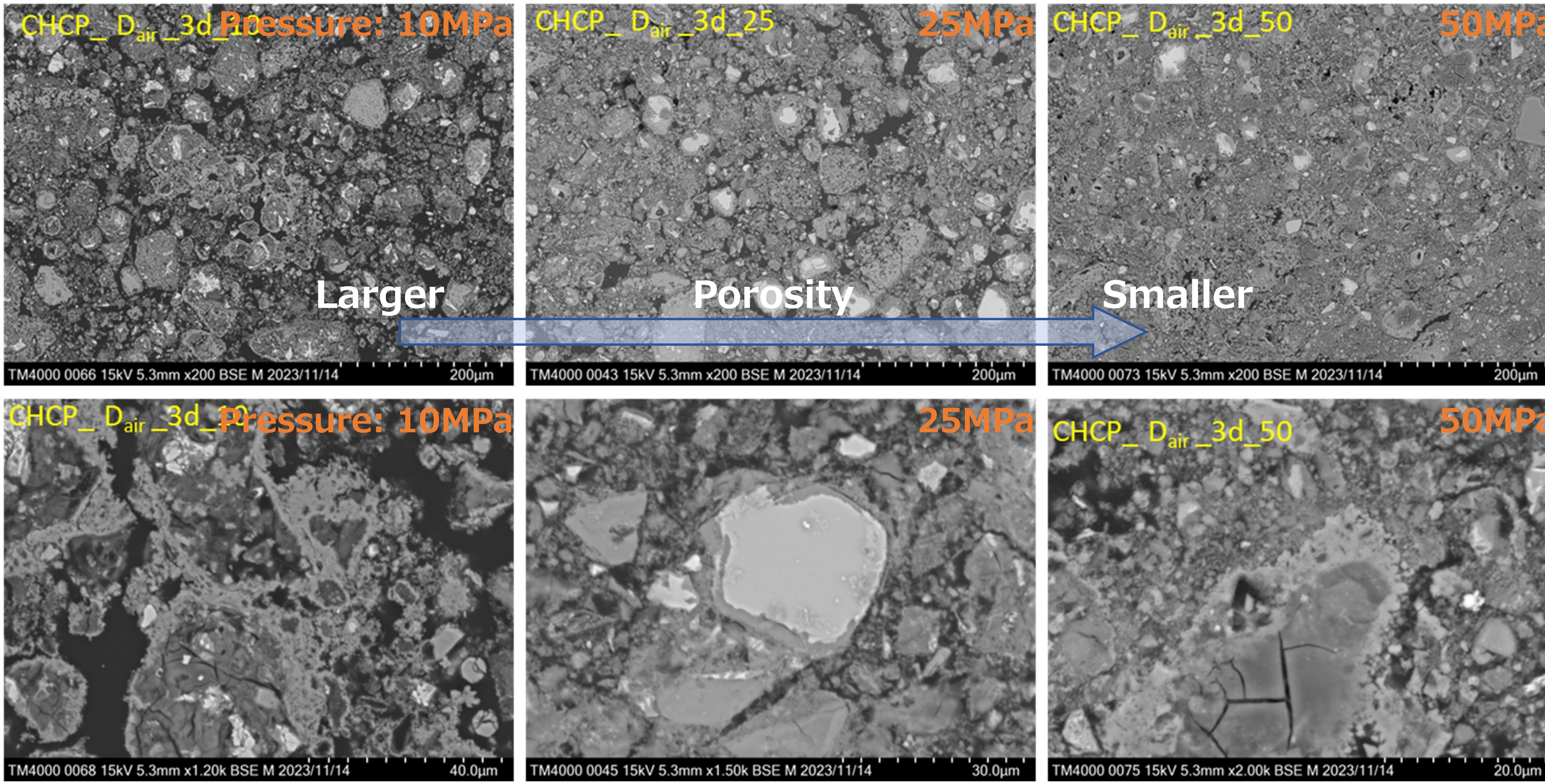




Larger size

Cold Sintering Method

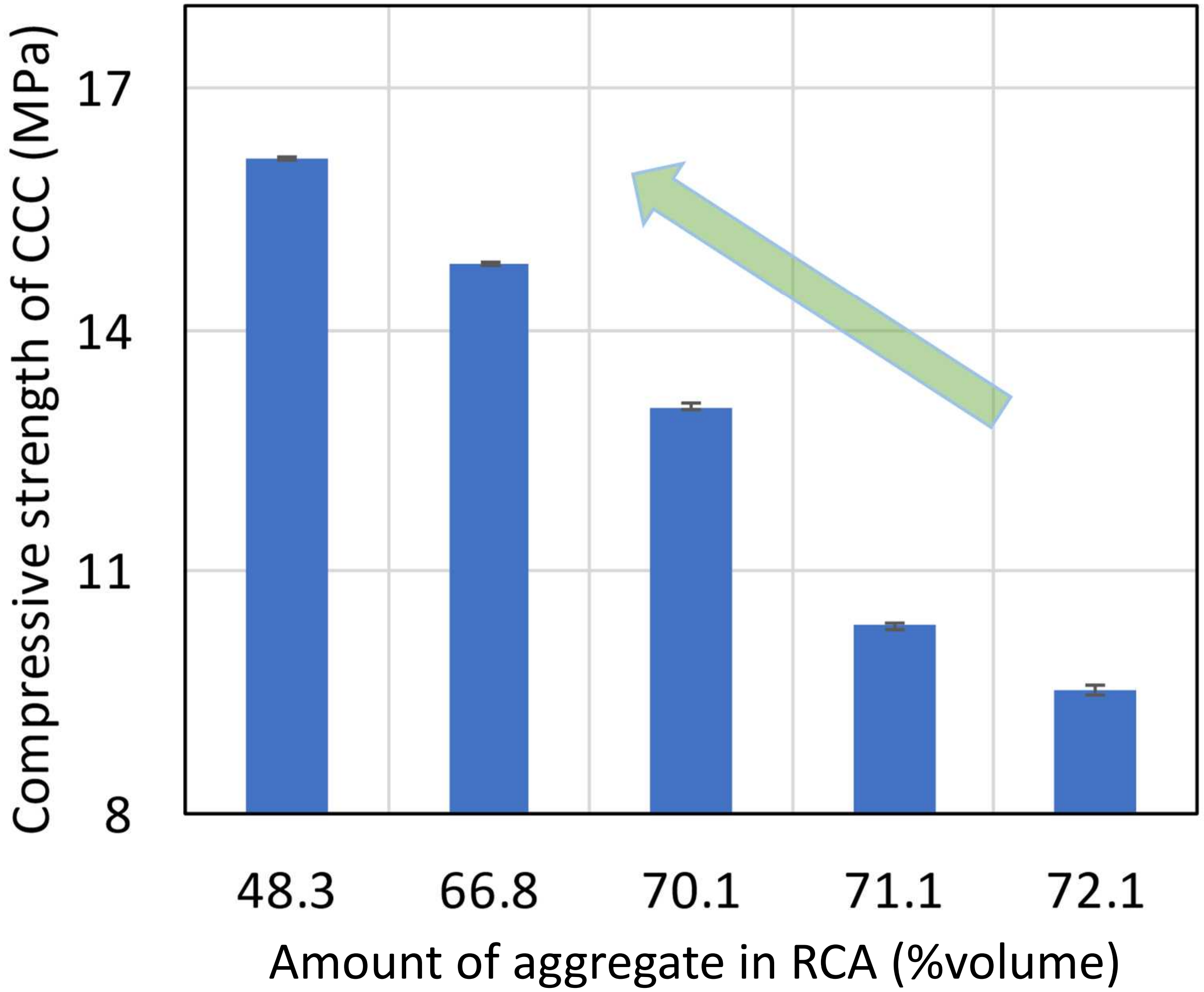
Effect of applied pressure



- Increasing pressure decreases porosity and increases compressive strength of CCC.

Effect of Raw Material on CCC Strength

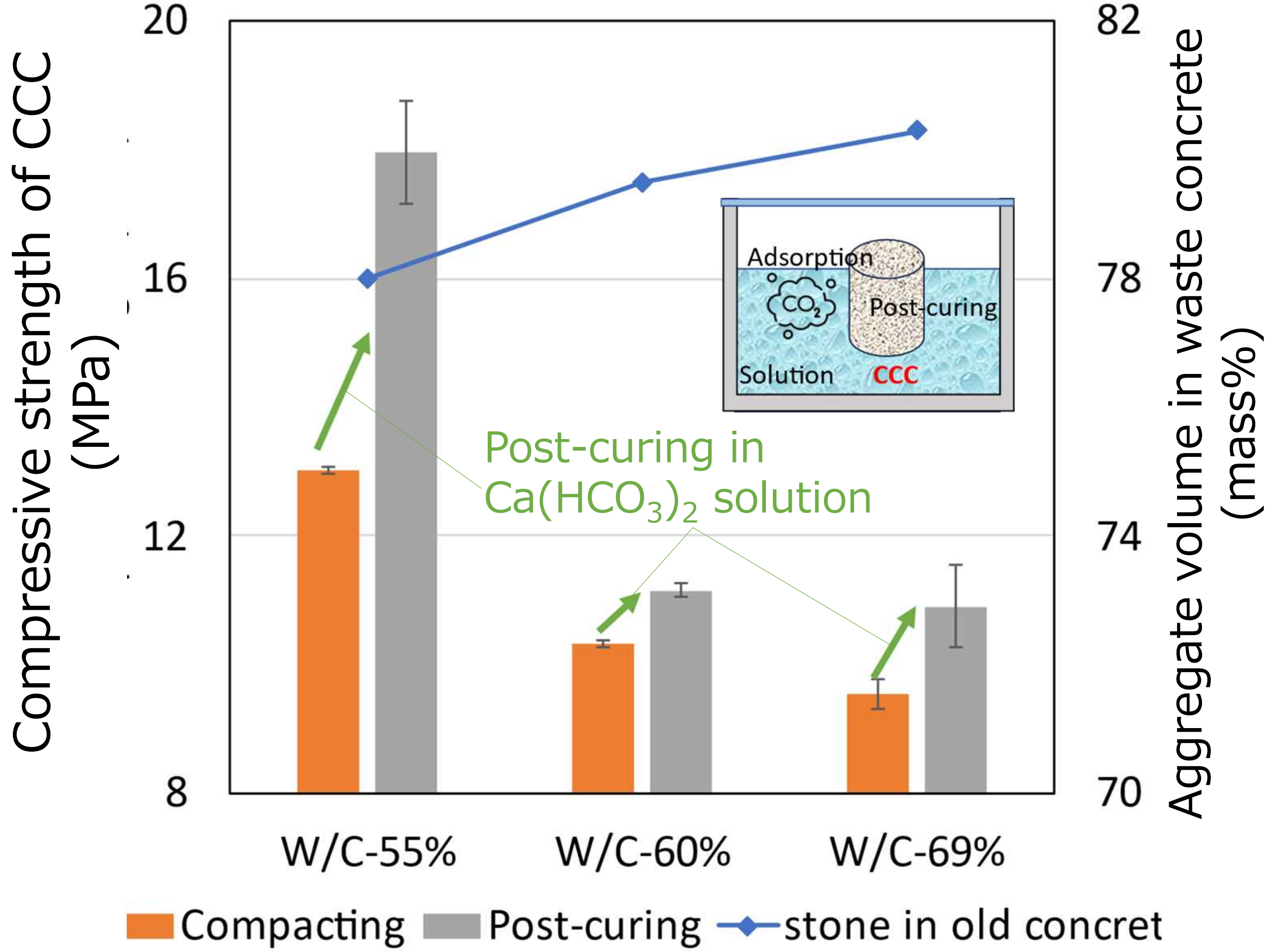
Effect of aggregate content in waste concrete (mother concrete)



■ The lower the amount of aggregate in the waste concrete → The higher the compressive strength of the CCC

Effect of Raw Material on CCC Strength

Effect of strength of waste concrete (mother concrete)
Effect of post-curing of CCC

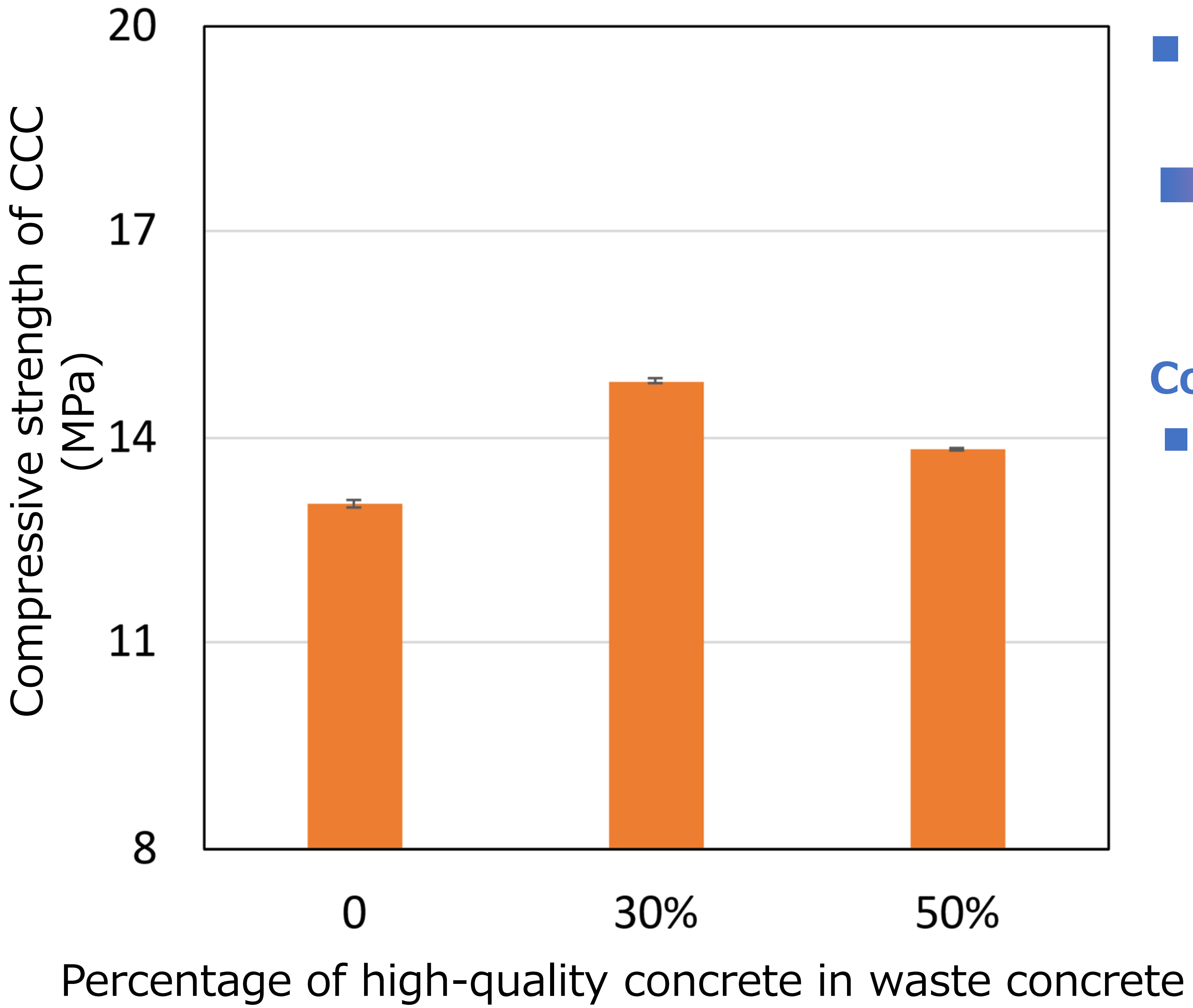


- Compressive strength of waste concrete (mother concrete) is high
- Compressive strength of CCC increases with post-curing

- Compressive strength of CCC is high
- Post-curing is highly effective

Effect of Raw Material on CCC Strength

Addressing quality variations in waste concrete

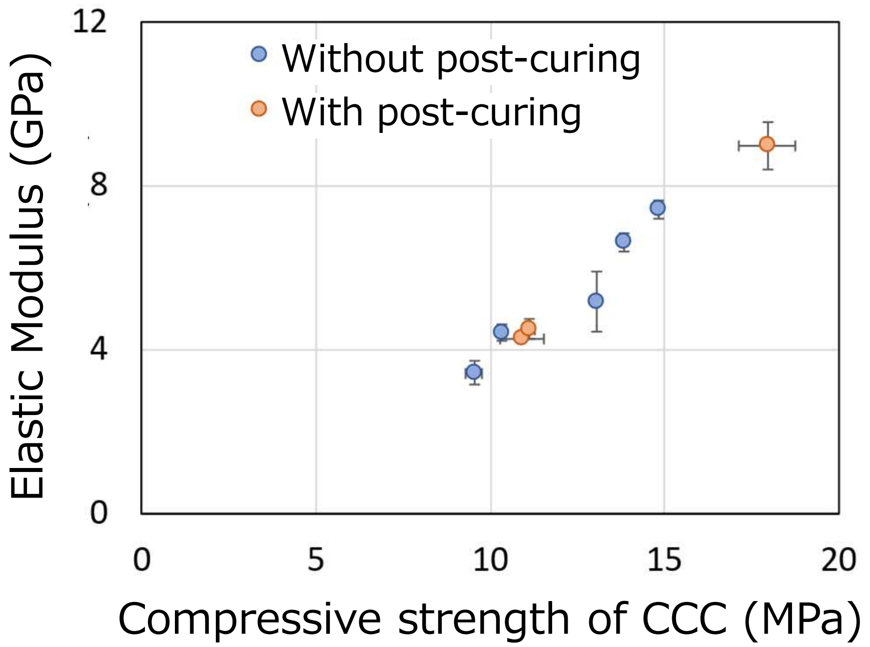


- Waste concrete (mother concrete) is of low quality

→ Improved strength by mixing with high-quality waste concrete

Compressive strength vs Other properties

- As with ordinary concrete, other properties can be controlled by controlling compressive strength



Practical Measures to Stably Produce CCC

- **Strength improvement measures** (**quality control**) when CCC is produced from low-strength (low-quality) waste concrete
  - Mixing of **more than 30%** of **high-quality** waste concrete (selective qualifying separation is required)
  - **Maximum size** of crushed waste concrete particles **0.6 mm or less**
  - Repeated soaking and drying in **$Ca(HCO_3)_2$ solution at least 6 times**

- If the volume of raw aggregate in the waste concrete is **less than 70%**, CCC with a compressive strength of **12MPa or higher** can be produced.

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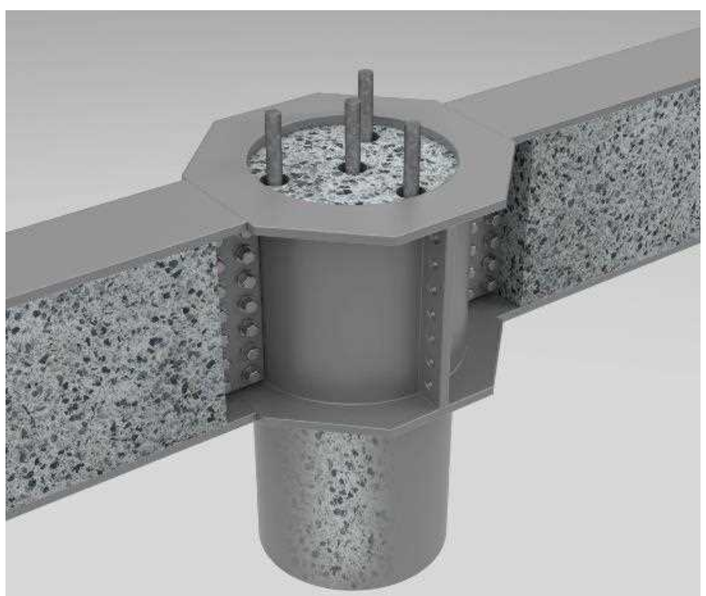
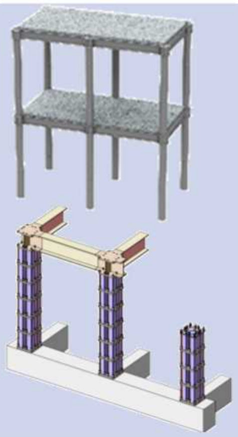
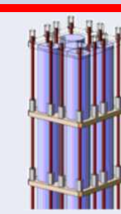
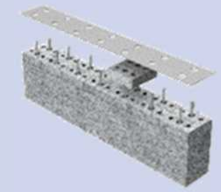
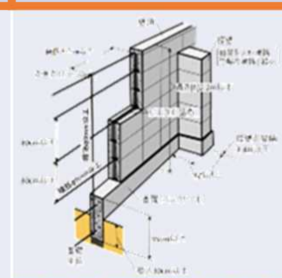
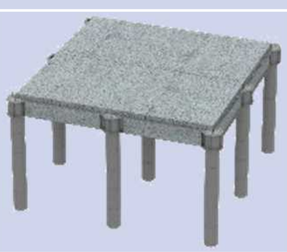
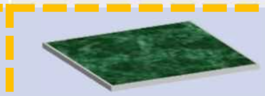
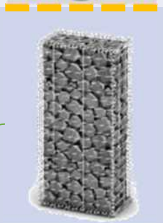
MOONSHOT RESEARCH & DEVELOPMENT PROGRAM

Development of Methods for Structural Design and Construction of CCC Structures



Structural Members Using CCC Units

Structural form		Members type and manufacturing method		Problems	Performance evaluation
Reinforced structure		Thin-walled steel tube + internal PS Stacking/Pressurization		Joints	Axial compression, bending, shear and joint
		Thin-walled steel tube + external PS CS/Pressurization/Precipitation		Joints	Axial compression, bending, shear and joint
Wall structure		Prestressed block CS/Pressurization/Precipitation		Prestressing	Axial compression, bending, shear and out-of-plane deformation
		Reinforced block (conventional) Interior: 20MPa and over Exterior: 30MPa and over CS/Pressurization/Precipitation		Reinforcing	Axial compression, bending, shear and out-of-plane deformation
Slab		Laminated		Manufacturing	Bending and shear
Beam and Joint		Steel composite		Manufacturing	Bending and shear
Cage filled		Cage filled			Axial compression, bending, shear and out-of-plane deformation

Verification by numerical analysis

Selected

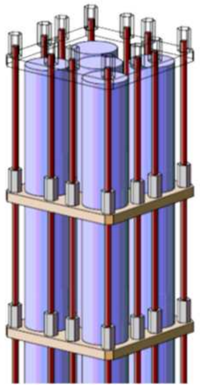
Study of overall structure

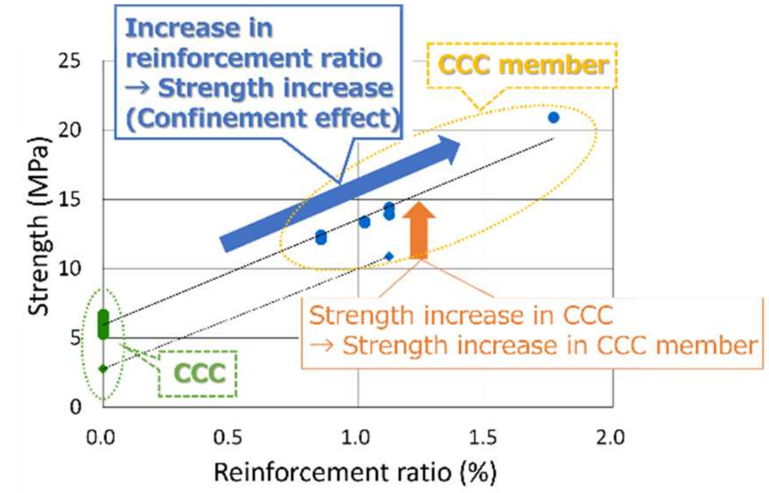
Investigation as wall structure

Structural Members Using CCC Units

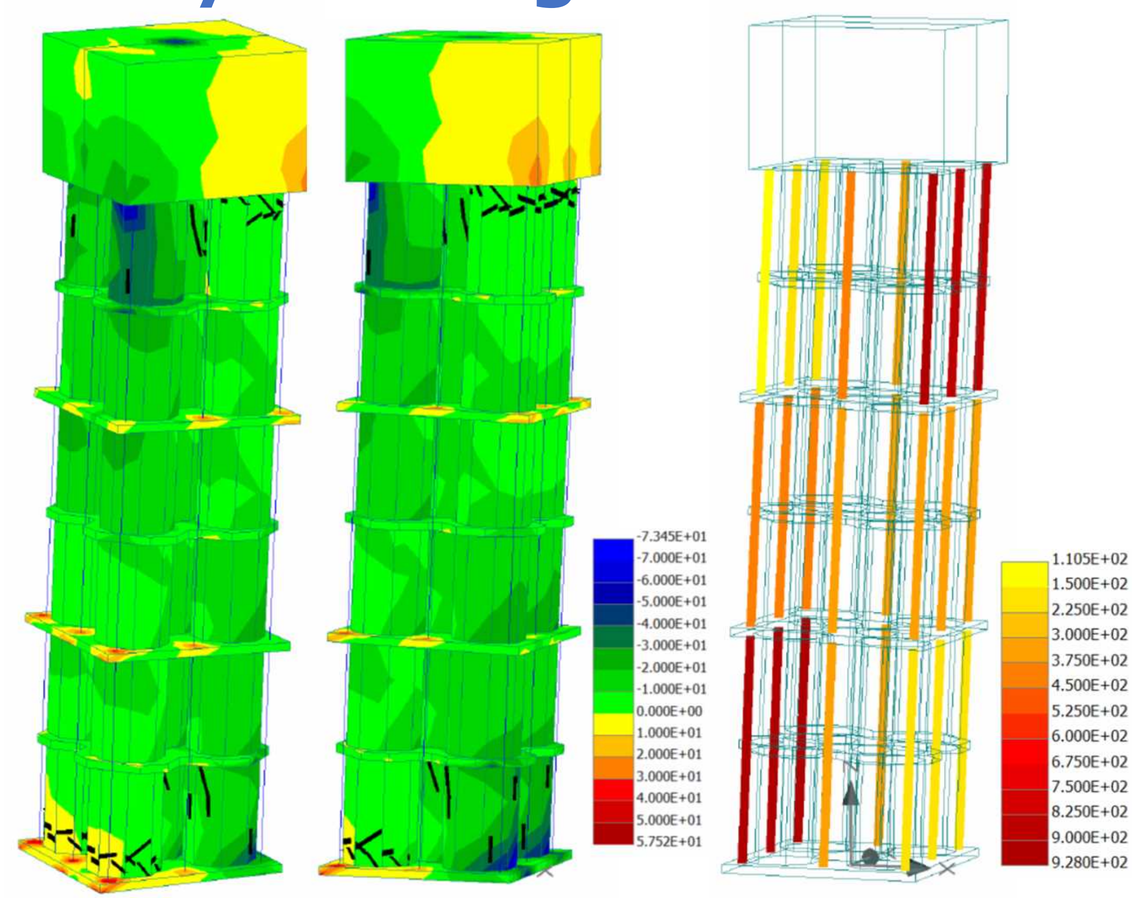
Thin-walled steel tube + external PS

- Improved strength by restraining thin-walled steel tube
- Verification and optimization of member performance by FEM analysis
- Demonstration test of member performance using a simulated CCC member

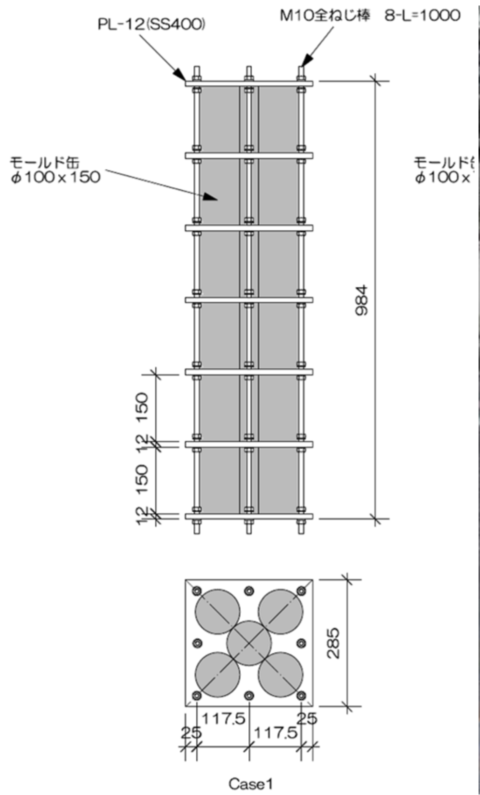




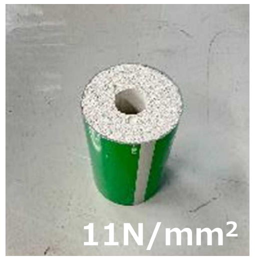
Analysis using FEM

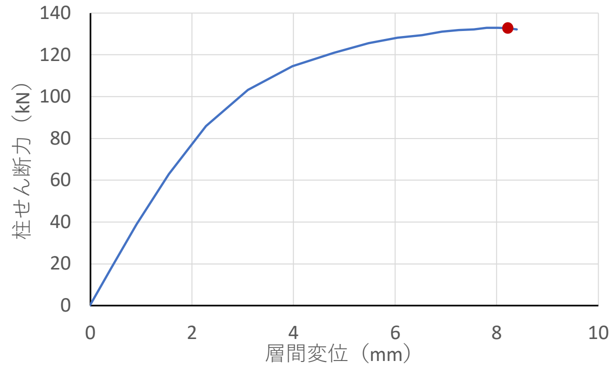


Experiments on simulated CCC columns



Simulated CCC column



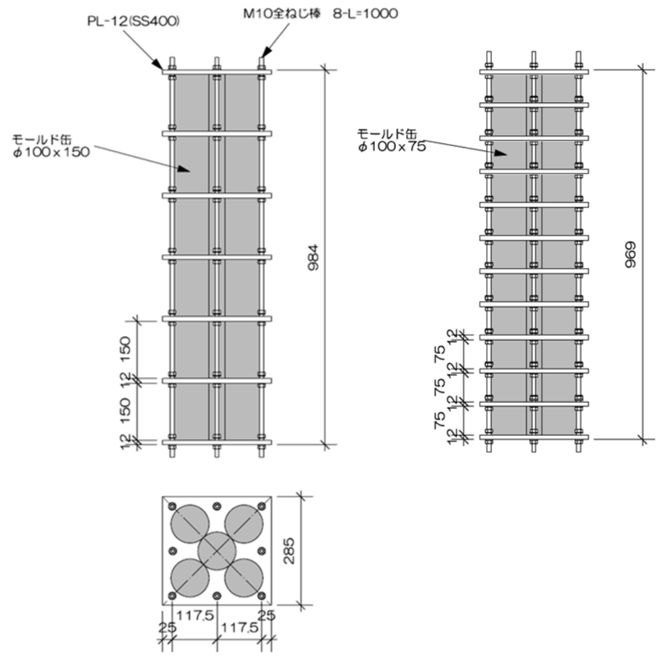


Axial force: 141kN（$0.15\sigma_B$）
Py=496kN（930N/mm²）
Prestress: 283kN (531N/mm²)
→CCC-7N/mm²（$0.30\sigma_B$）

Structural Members Using CCC Units

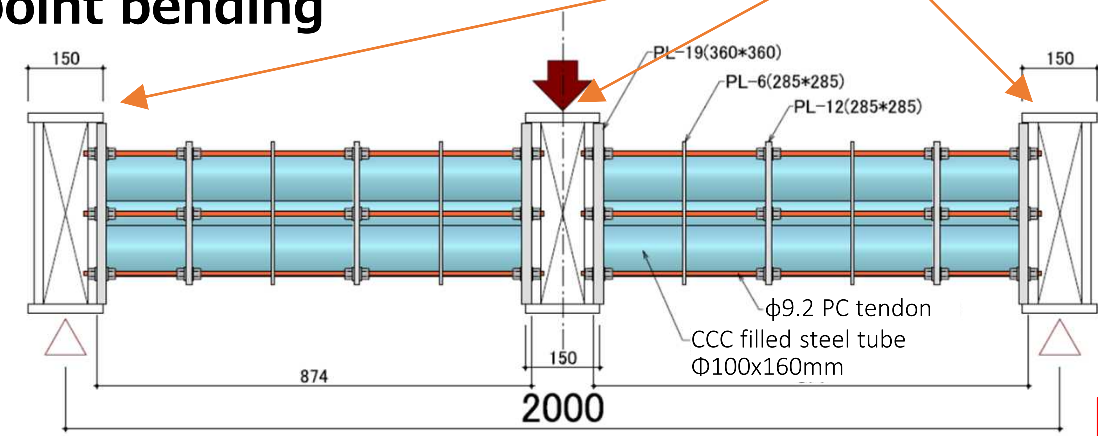
Evaluation of bearing capacity of simulated CCC members and CCC members

- Two units of different heights were prepared assuming the manufacturing process
- Three-point bending / Ohno's method reverse symmetry bending shear



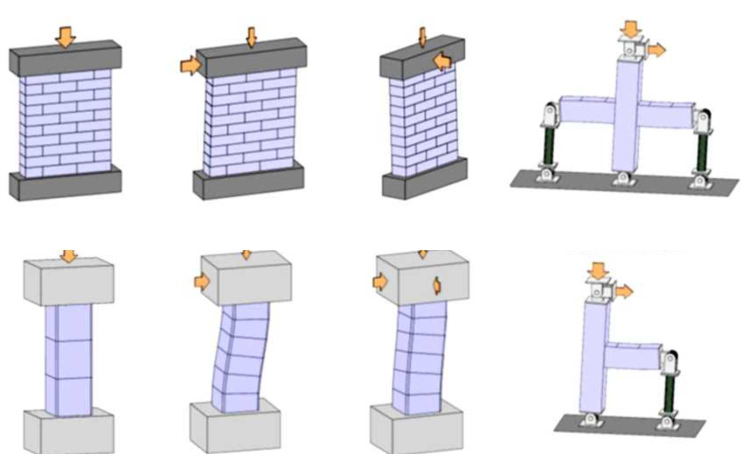
For thin steel tube and external PS type, change the loading area, etc.

Three-point bending

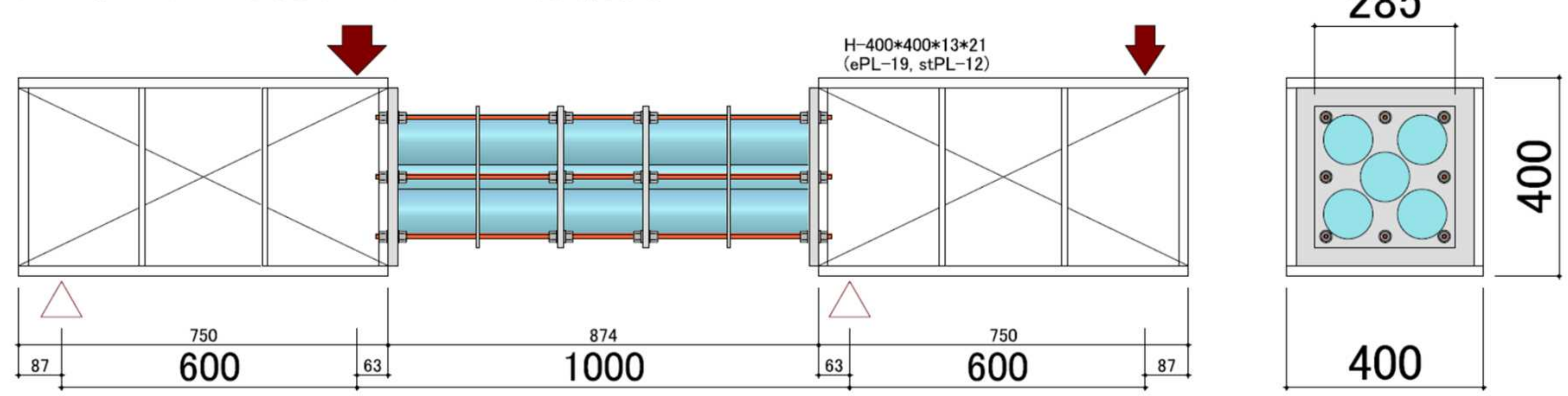


PC tension force: 35kN/piece
280kN for 8 pieces

Candidate for performance evaluation tests in the future



Ohno's method reverse symmetry bending shear



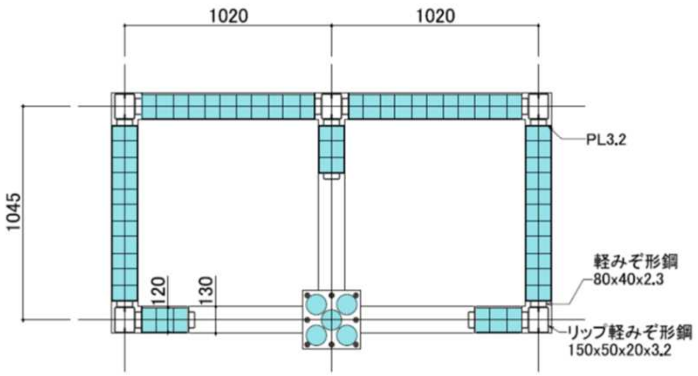
Structural Members Using CCC Units

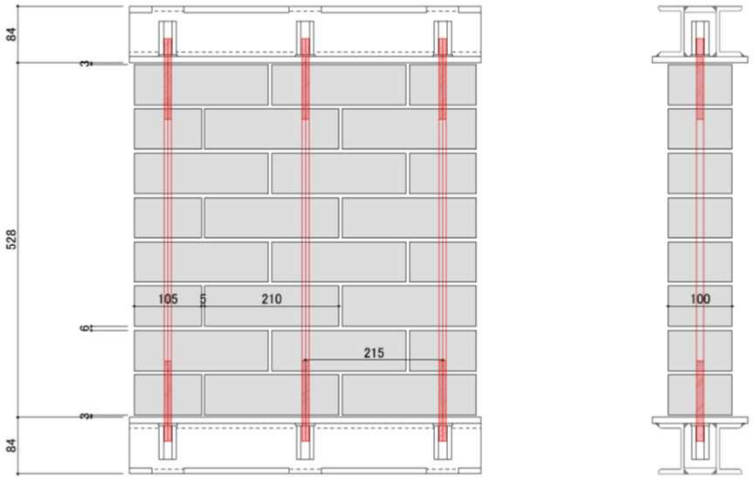
Overall structure using CCC members

- How to join members
- Optimal use of CCC

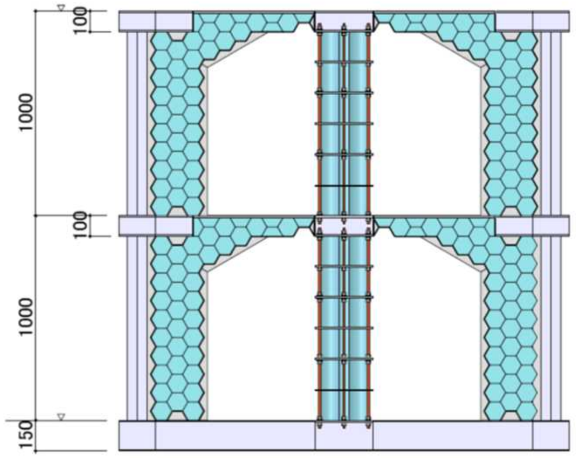
Prestressed block structure

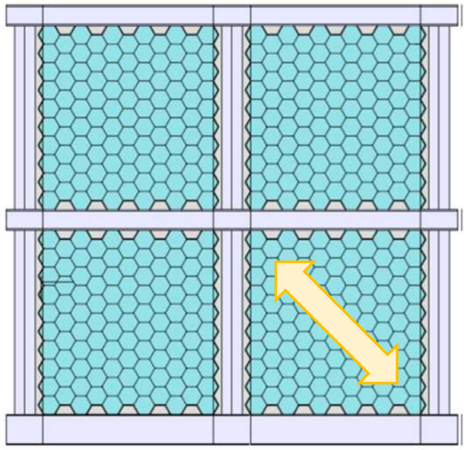

W/C=100%, C:S=1:3
Mortar block with viscous agent

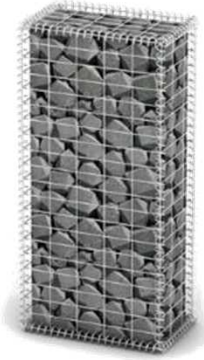


Arch (compression only)





Honeycomb construction



Cage

The University of Tokyo
Hokkaido University
Tokyo University of Science
Kogakuin University
Utsunomiya University
Shimizu Corporation
Taiheiyo Cement
Masuo Recycle

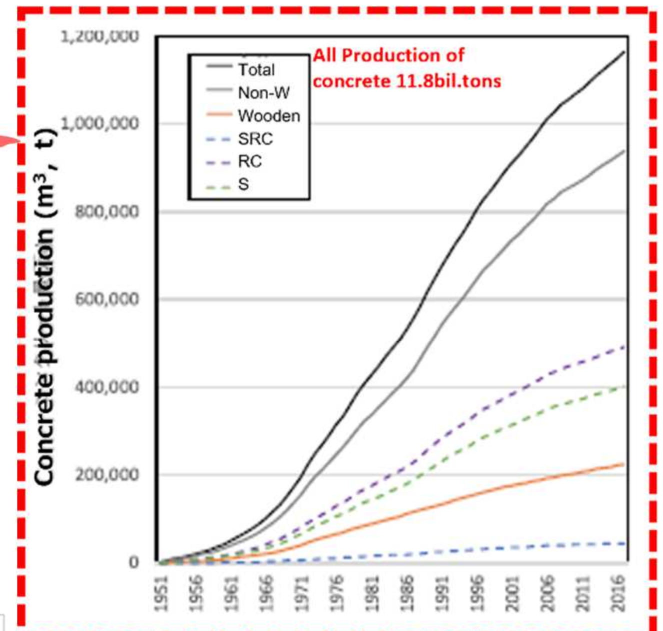
Social Implementation of C^4S

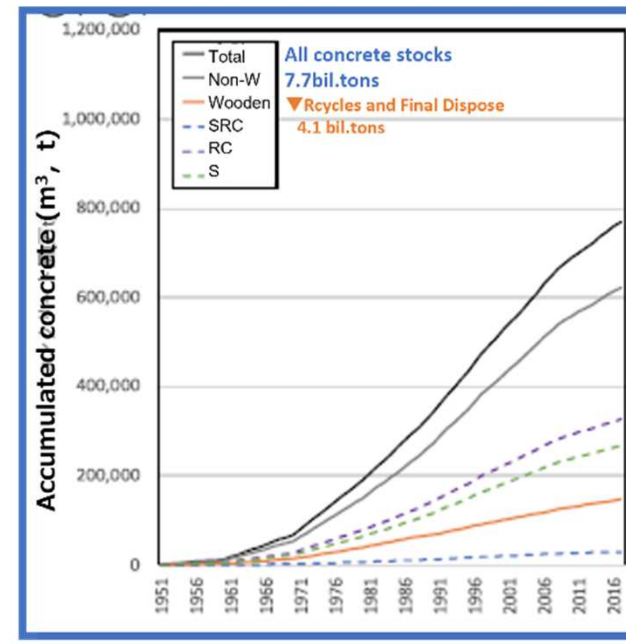
Resource Circulation Scenario Design

①Conducting research and estimation on the amount of waste concrete generated (CCC raw materials) based on regional characteristics
②Planning of efficient intermediate treatment plant layout, development of types, characteristics, and acceptance conditions of waste concrete, and presentation of newly required production system updating methods
③Construction of resource circulation scenarios based on CCC applications (structure type, site, and product) and conditions for waste concrete discharge and treatment

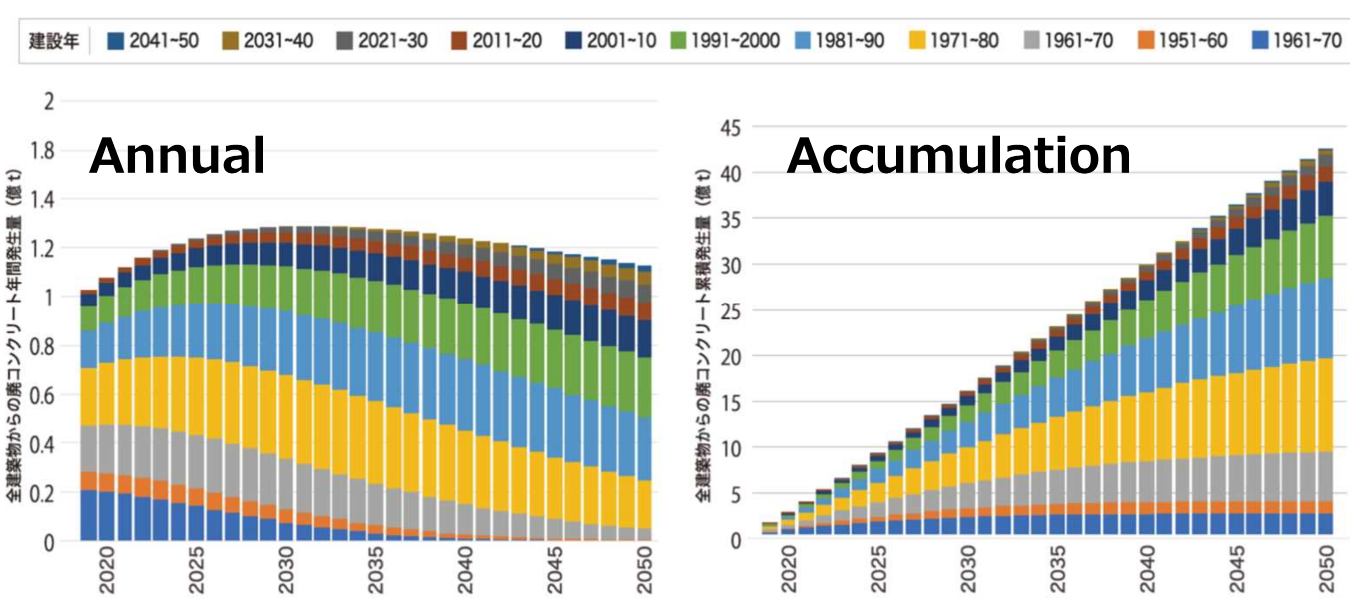
①Prediction of the amount of CCC raw materials accumulated and generated

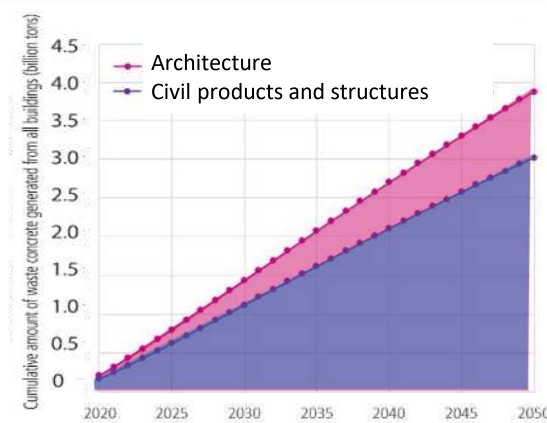
Construction Input!





Cumulative concrete production for all construction starts: 11.8 billion tons
■By structure: RC 38.3%, S 33.3%, wood 19.2%, SRC 8.5%
■By region: comparison by city (Kanto/Kansai), by prefecture (all 47), etc.
*Recovered ready-mixed concrete statistics (METI): Historical production volume: approx. 30 billion tons (construction 40%, civil engineering 60%)





Waste concrete generated (2020-2050: 30 years)
Buildings: 3.9 billion tons (0.126 billion tons/year in average)
Products: 3.0 billion tons (0.1 billion tons/year in average)

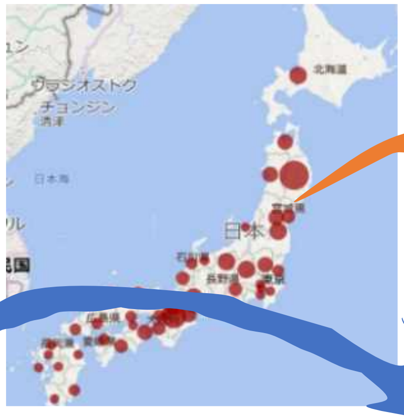
Resource Circulation Scenario Design

②Siting plan for an intermediate treatment plant to facilitate CCC production

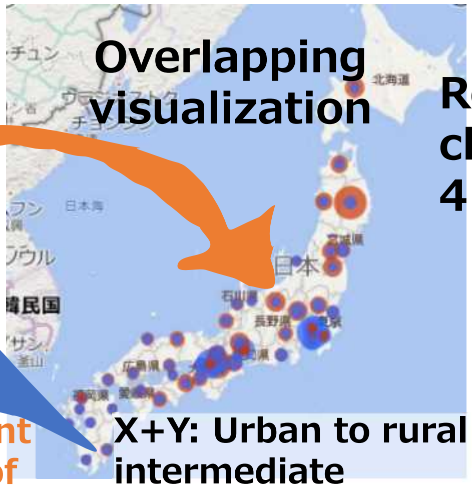
Classification B = CCC generation by urban - specialized processing areas x Selection of manufacturing sites

Mapping of intermediate treatment plants (N) by prefecture

Y: Intermediate treatment plant relative treatment volume range (man/facility)

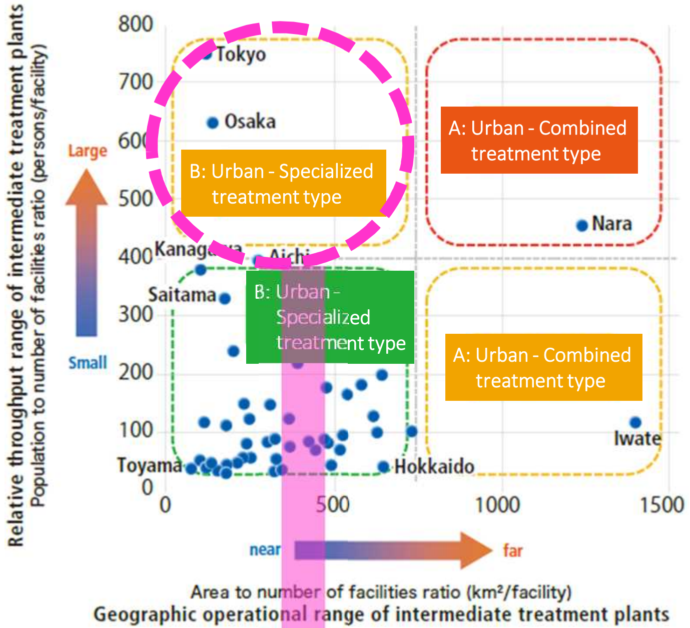


X: Intermediate treatment plant geographic scope of work (km²/facility)

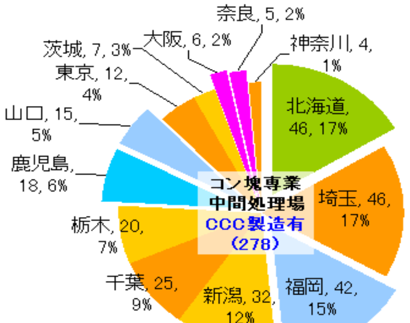


X+Y: Urban to rural intermediate treatment classification (ABCD)

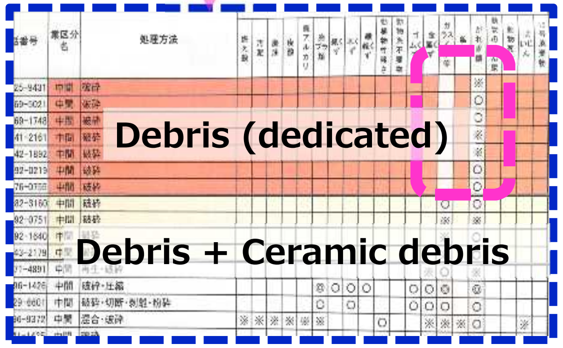
Regional characteristics 4 classification



Database of information on industrial waste treatment by prefecture (certified excellent companies) + intermediate treatment facilities specializing in concrete mass (CCC production sites)



Candidate for CCC manufacturing site



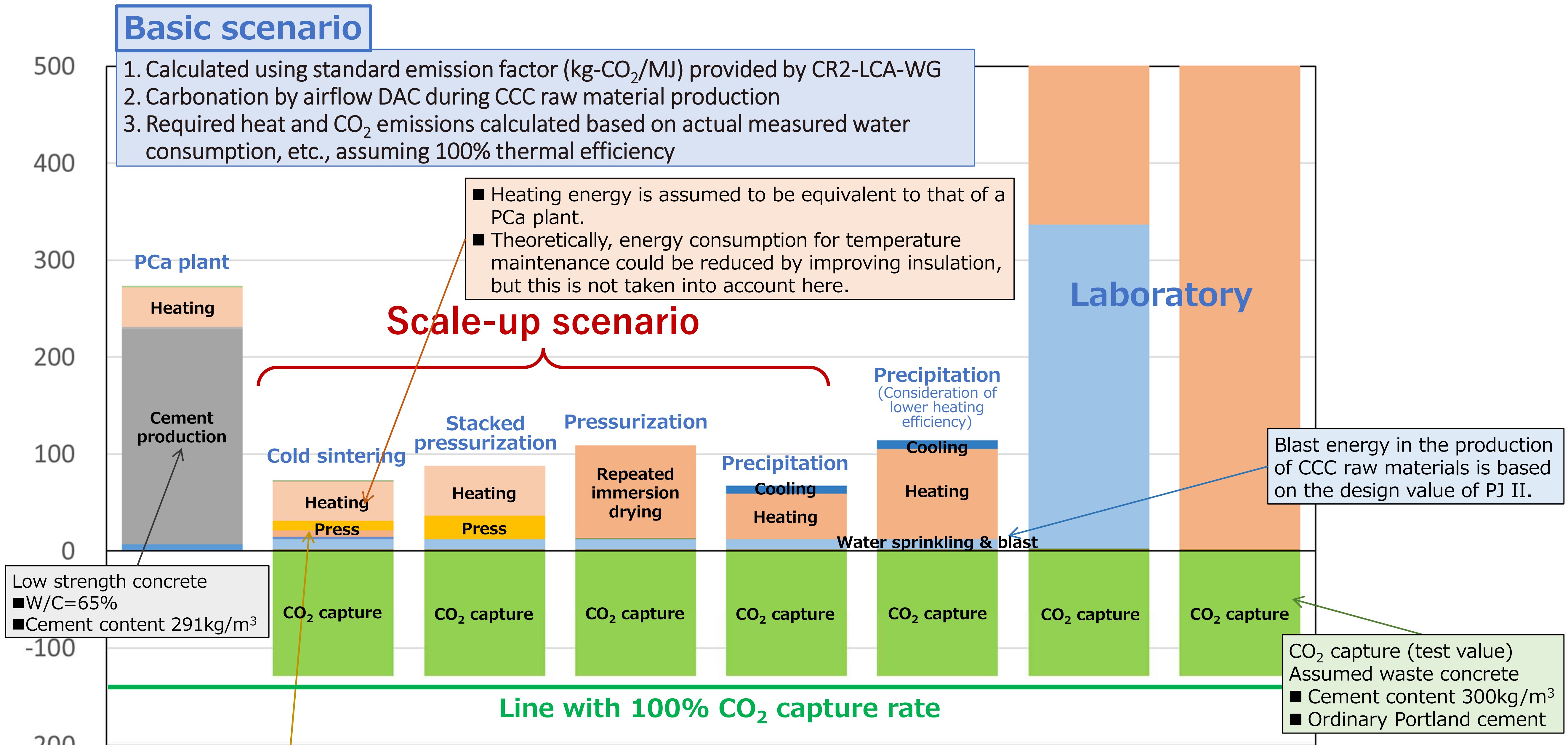
Results

- ■Estimation of the **amount of concrete mass generated by prefecture** by 2050
- ■Identification of **excess and deficient treatment capacity of intermediate treatment plants** by prefecture
- ■Establishment of **four regional classifications** by **potential treatment capacity** and **physical treatment area** of intermediate treatment plants by prefecture
- ■Identification of the number of possible facilities in "CCC production base areas"

Future Issues

- ■Understanding of **conditions for installation of intermediate treatment plants**, etc. under several laws
- ■Development of **optimal intermediate treatment systems** and **manufacturing technologies for PCa plants**

Estimation of CO_2 Emission



■ For pressurization energy, refer to the basic unit for tile production (wet type)
■ CCC unit: 210x100x60mm, 5 pressurizations/unit to produce 1m³
■ Assuming 5 units pressurized in series for efficiency

■ Mixing energy for CCC production is assumed to be the same intensity as that of concrete
■ Vibratory compaction is assumed to be equivalent to the repeated immersion method
■ Solution production is assumed to be equivalent to that of ready-mixed concrete and sludge tanks.

Examination of Systems on Building Codes

① When it can be regarded as equivalent to ordinary concrete

- Designated building material (Article No.37 of the Building Standard Law)
  - Available as JIS A 5308 compliant product
  - Evaluated according to the current public notice, and available after obtaining the approval by the Minister of Construction
  - Can be evaluated by modifying the public notice, and can be used after obtaining the approval by the Minister of Construction

② Similar to but not considered equivalent to ordinary concrete

- Categorized in the definition of concrete (JIS A 0203)
- Positioned as a designated building material
- Newly positioned as "special concrete" in the public notice and need to be evaluated

③ Different from (not similar to) ordinary concrete

- Not a designated building material

In case of CCC: ③

- **Individual approval by the Minister of Construction as stipulated in Article No.20 of the Building Standards Act is required for design methods, quality control, etc.**

Participating in the "**Environmentally Friendly Concrete Response Study Committee**" of the Japan Building Disaster Prevention Association

- Ministry of Construction-subsidized project "Project for Ensuring Smooth Enforcement of the Building Standard Law, the Building Official Law, etc.”
- Chairperson: Takafumi Noguchi, Committee members: Manabu Kanematsu, Ippei Maruyama, etc.

Plans for Construction of Actual Structures

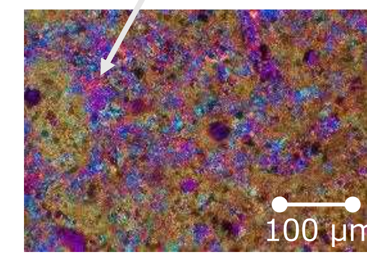
■ Exhibit at Future Society Showcase Project at Osaka Expo

https://www.expo2025.or.jp/en/news/news-20230914-01/

→Application for 13m² periodic exhibitions in the Future Life Experience

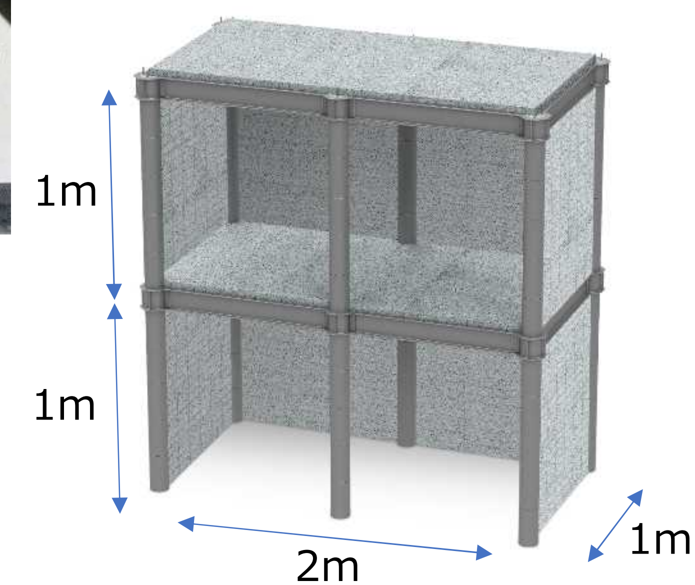
CCC raw materials

Precipitation of $CaCO_3$ (≒CO_2)



Visualization of CO_2 in CCC化

CCC units



Structure using CCC
(Shape to be further elaborated)

Thank you for your kind attention!

To realize a carbon neutral society in 2050, we will continue to study the social implementation of CCC in FY2029.