MODIFICATION ON RECYCLED AGGREGATES AND ITS INFLUNCE ON RECYCLED CONCRETE

Kaiwen Huang, Tao Ding
Jianzhuang Xiao, Amardeep Singh
Tongji University

Contents

1 Background

2 Optimization of production process

3 Modification on recycled aggregates

4 Conclusion

Background

The source of waste concrete

Lanzhou zhongli bridge
(Age:13 years, Date: July 5, 2010)

Shanghai "The first bend in Asia"
(Age:11 years, Date: February 13, 2008)

Background

Waste concrete bring about a series of problems

- Growing emission of waste concrete
- Growing shortage of natural aggregate and high mining and transport energy consumption

↓

- How to deal with the waste concrete?
- How to save the natural resources?

↓

But waste concrete can't be applied to construction directly. The quality of recycled aggregates is lower than natural one.

↓

How to modify the recycled aggregates?

Optimization of production process

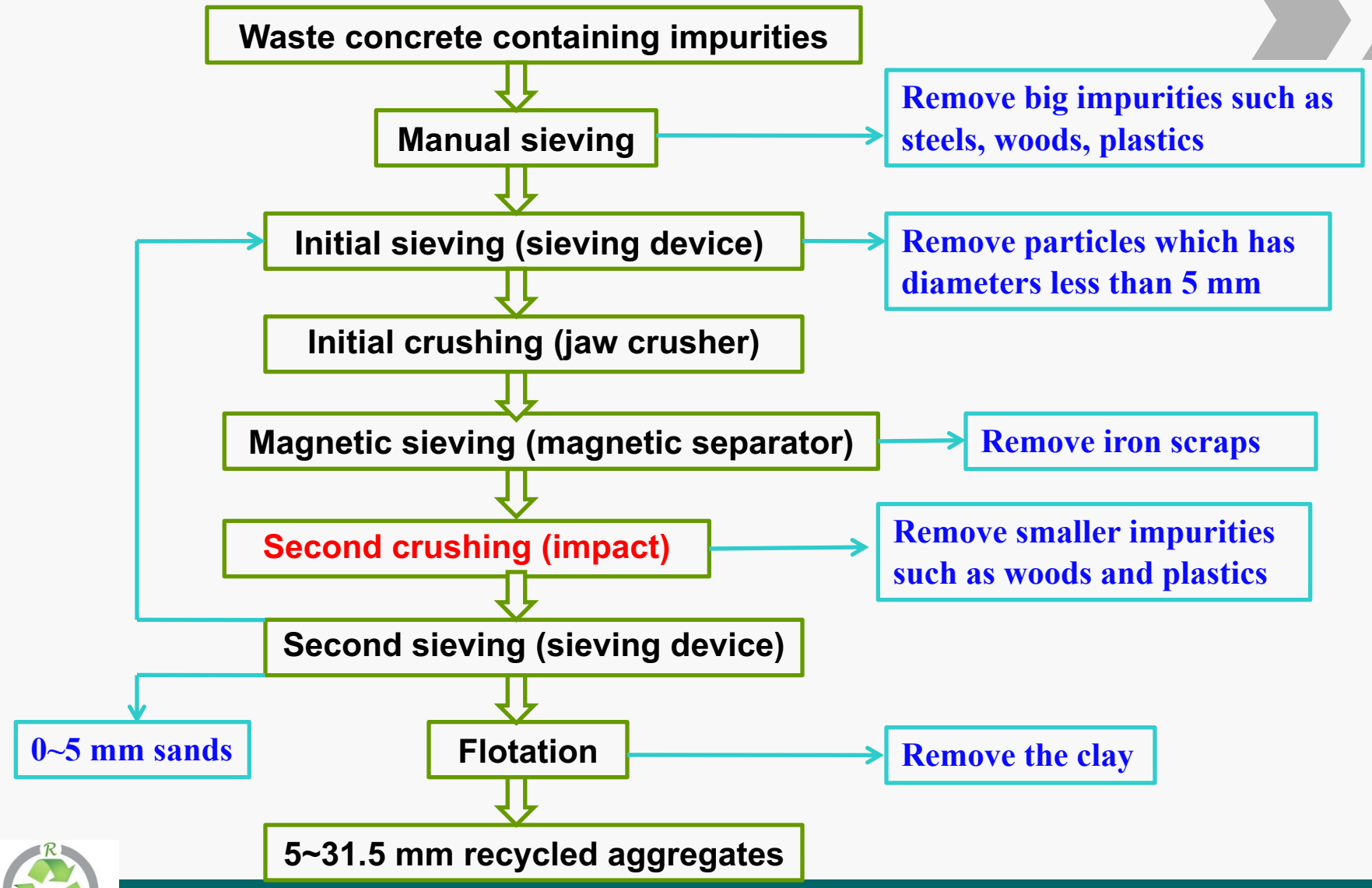
Optimization of production process

Production line of recycled aggregates

Optimization of production process

Production line of recycled aggregates

Proposed production process



Optimization of production process

Recycled aggregates from the production line

Recycled aggregates (Relatively pure)

Recycled aggregates (Containing red bricks)

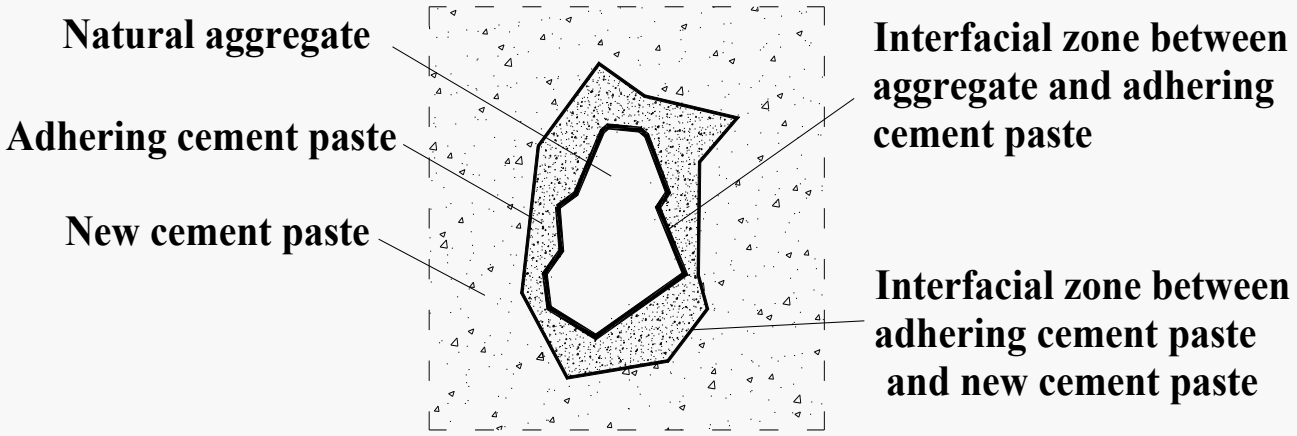
Properties of natural aggregates and recycled aggregates

Type of aggregates	Bulk density (kg/m^3)	Apparent density (kg/m^3)	10min water absorption rates (%)	Porosity rates (%)	Crushing index value (%)	silt content (%)
NCA	1453	2820	0.332	1.1	4.04	1.8
RCA	1290	2520	8.34	23.3	15.2	4.08

Optimization of production process

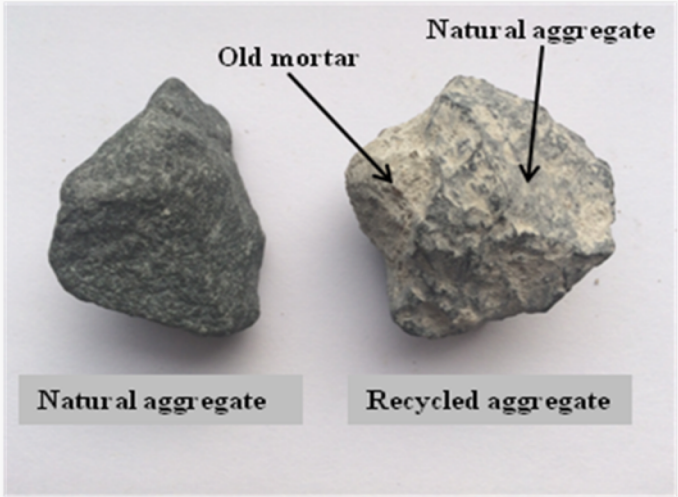
Compared with natural aggregates, recycled aggregates have the following properties:

- **Lower apparent density, bulk density**
- **Higher porosity**
- **Higher clay content**
- **Higher water absorption**
- **Higher crushing index value**



Schematic diagram of recycled aggregate

Modification on recycled aggregates



Remove or fix

Modification on recycled aggregates

- The modification of recycled aggregates is the most important part, which will greatly influence the strength and durability of the recycled concrete.
- Here we will introduce the following 3 types of technology:

➢ **Physical technology**

Remove the adhered cement pastes by mechanical forces or heat.

➢ **Chemical technology**

Cover the adhered cement pastes by immersing recycled aggregates into specific chemical grout.

➢ **Carbonation technology**

Improve the density of attached cement pastes by carbonation reaction.

Physical technology

1. Vertical eccentric grinding method

- Put the recycled aggregates into the vertical eccentric grinding equipment, under the high speed rotation of inner eccentric wheel, cement paste adhered to recycled aggregates will be removed, so are the recycled aggregates' protuberant edges.

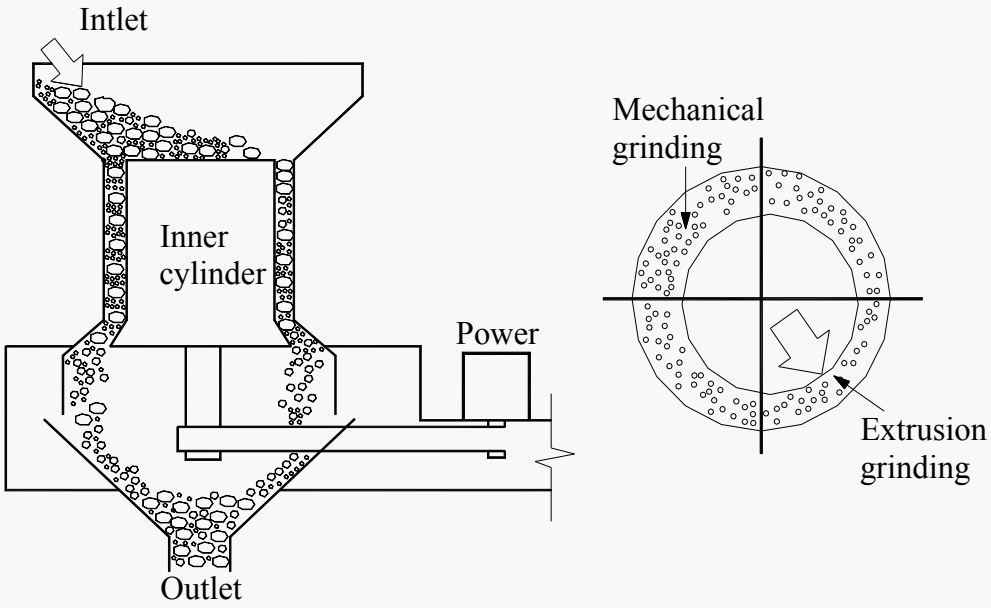


Fig. 2 Vertical eccentric grinding equipment

Yanagibashi K, Yonezawa T, Arakawa K, et al. A new concrete recycling technique for coarse aggregate regeneration process[J]. Thomas Telford, 2002.

2. Horizontal gyration grinding method

- When recycled aggregates that need to be modified are put into the horizontal gyration grinding equipment, under the interaction effects of grinding blocks, lining plates and aggregates, the strength of recycled aggregates will be improved .

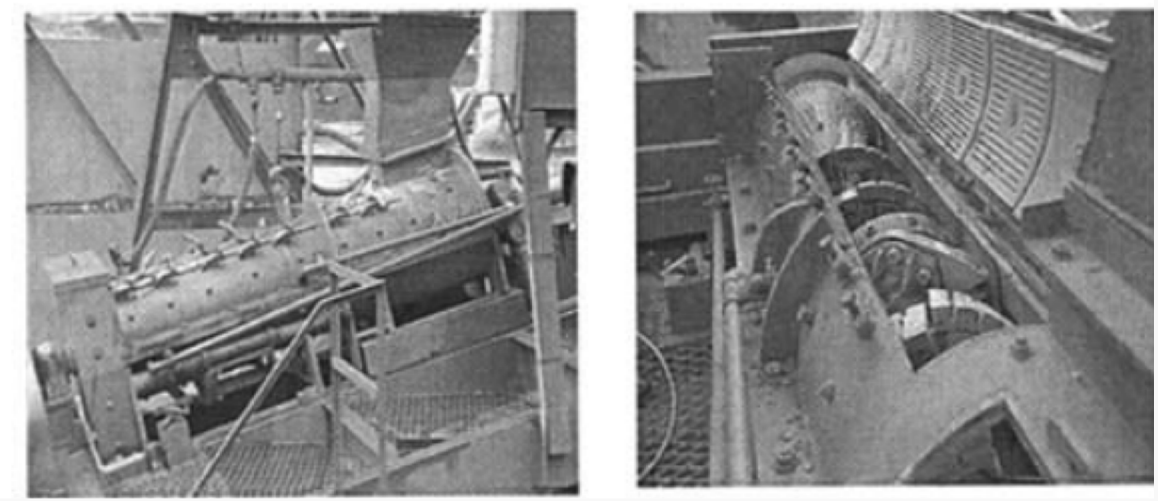


Fig.3 Diagram and internal structure of horizontal gyration grinding equipment

李秋义, 李云霞, 朱崇绩,等. 再生混凝土骨料强化技术研究[J]. 混凝土, 2006(1):74-77.

3. Abrasive grinding method

- **The use of ball mill or rod mill to remove effectively the adhering hardened cement pastes can produce high quality recycled aggregates; this idea can be described as abrasive grinding method.**

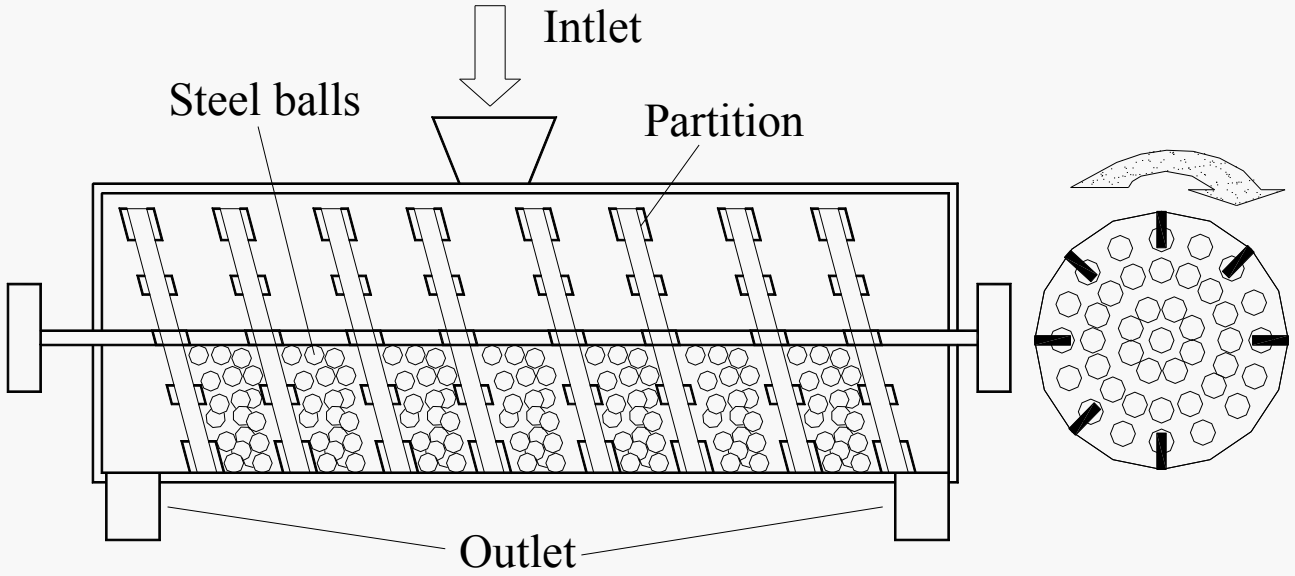


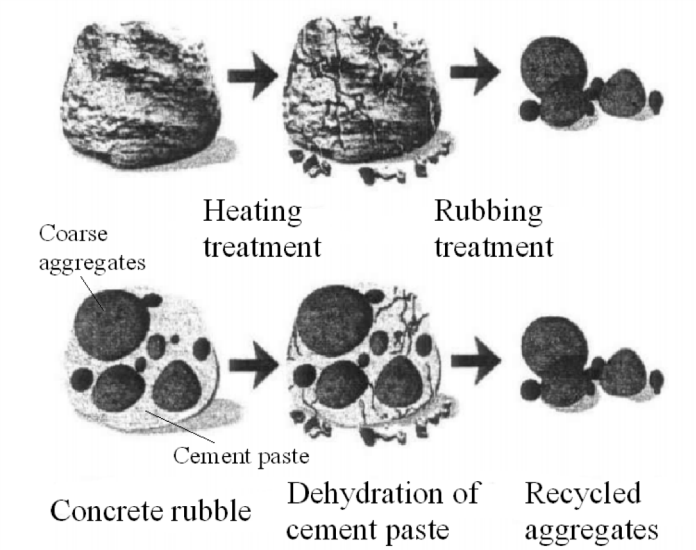
Fig.4 Ball milling equipment of abrasive grinding method

Quattrone M, Angulo S C, John V M. Energy and CO 2, from high performance recycled aggregate production[J]. Resources Conservation & Recycling, 2014, 90(7):21-33.

Physical technology

4. Heating and rubbing method

- The preliminary crushed concrete blocks were heated to 300~400℃ to make cement pastes brittle with their dehydration, then the concrete will be rubbed in two equipment to strengthen the recycled aggregates



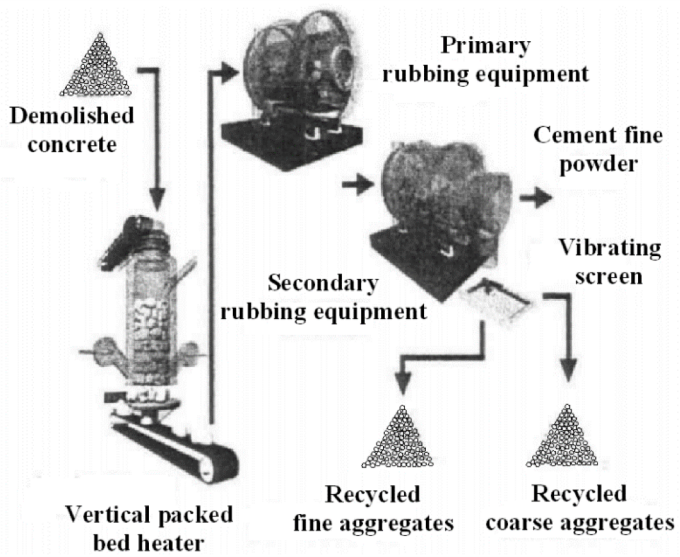
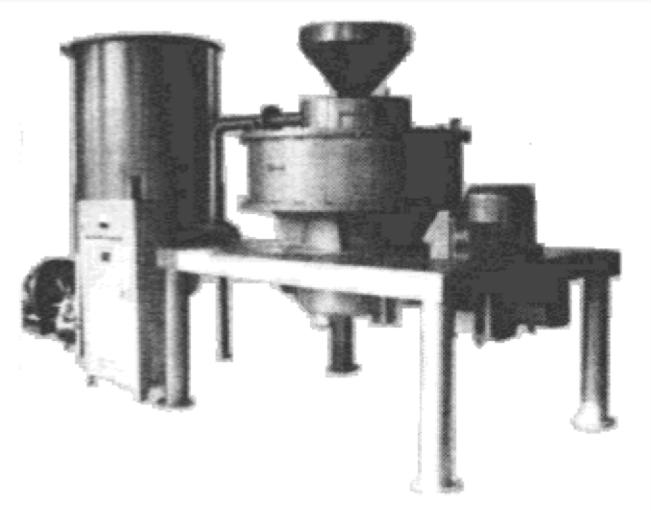


Fig.5 Heating and rubbing method

✓ 再生骨材を用いるコンクリートの設計・製造・施工指針（案）
✓ SHIMA H, TATEYASHIKI H, MATSUHASHI R, et al. An advanced concrete recyc1ing technology and its applicability assessment through input-output analysis[J]. Journal of Advanced Concrete Technology, 2005, 3(1): 53-67.

5. Particle shaping method

- Recycled aggregates put into the particle shaping equipment will collide with each other. After several times' collisions the recycled aggregates will have smooth surface, good particle shape, and the bulk density will be improved with higher purity



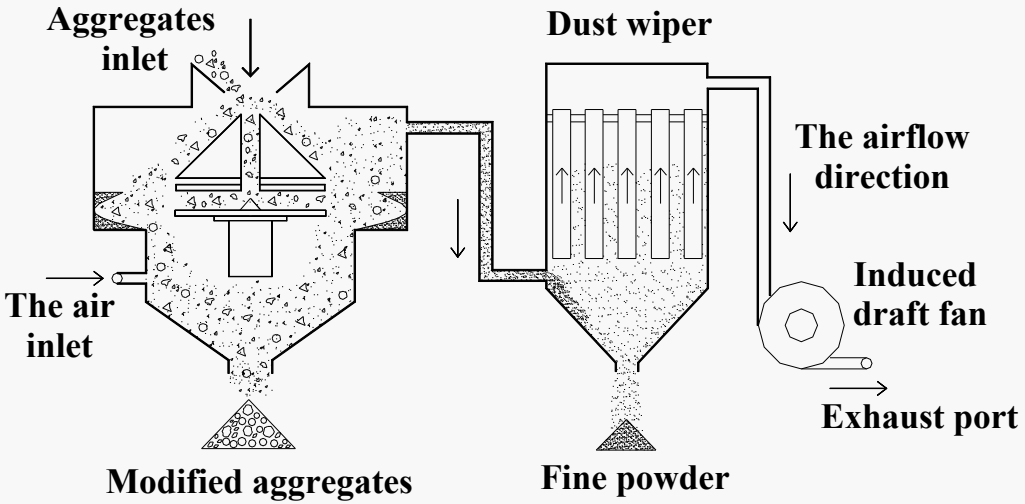


Fig.6 The configuration and structural diagram of the particle shaping equipment

➢ LI Qiu-yi, LI Yun-xia, ZHU Chong-ji, TIAN Li. Strengthening technique of recycled concrete aggregate[J]. Concrete, 2006(1): 74-77.

6. Microwave-assisted method

- A novel microwave-assisted method may be effectively used to partially remove the adhering cement paste by developing high temperature gradients and high thermal stresses within the mortar, especially at the interfacial zone with the gravels.

Fig.7 Pilot microwave heating system used for experimental program

- 肖建庄,吴磊,范玉辉. 微波加热再生粗骨料改性试验. 混凝土, 2012, (7): 55-57.
- A. Akbarnezhada, K.C.G. Onga, M.H. Zhang. Microwave-assisted beneficiation of recycled concrete aggregates[J]. Construction and Building Materials, 2011(25): 3469-3479.

Physical technology

- **Summary of physical technology**

With the assistance of the mechanical/heat forces to remove the adhering old cement pastes, then the modified recycled aggregates have high purity of gravels. However, this technology has the following disadvantages:

- Consume more energy and resources;
- Demand complicated equipment;
- High cost.

Therefore, physical technology is not suitable for all cases. Even so, the current recycled aggregates modification is mainly by physical technology.

Chemical technology

- Chemical technology is mainly about immersing recycled aggregates into specific chemical grout, which will cohere or fill the micro-cracks or micro-pores.
- This technology achieves the purpose of modification by changing the chemical composition of recycled aggregates' surface and makes them denser or improves their strength.

The available chemical grout can be listed as follows:

1. Polymer emulsion

- Polymer emulsion solution can be used to improve the properties of recycled aggregates, especially recycled fine aggregates.

- The tests of mortar blocks made of recycled fine aggregates after the modification of polymer emulsion solution showed that: the flexural strength improved obviously, while the compressive strength has little improvement.

Chemical technology

2. Mixed cement grout

- *Neat cement grout*
- *Cement grout with additive Kim powder*
- *Cement grout with additive silica fume*
- *Cement grout with additive fly ash*
- *Cement grout with additive di-atomite硅藻土*

Cement grout or additives can fill pores or have chemical reaction with the cement hydration products in the recycled aggregates, this process will influence the property of water absorption.

Chemical technology

Experiment 1 and experiment 2 studied the strengthening of recycled aggregates by using cement grout with different kinds of high activated superfine mineral additives.

Results of Experiment 1

Chemical grouts	Physical properties of RA				Mechanical properties of recycled concrete	
	Water content /%	Water absorption rates /%	Apparent density /(kg/m^3)	Crushing index value /%	60d compressive strength (MPa)	Growth rate of strength /%
untreated	2.82	6.68	2424	20.6	36.6	0
Neat cement grout	4.69	9.65	2530	17.6	37.7	3.01
Cement grout with additive Kim powder	1.87	8.18	2511	12.4	40.7	11.20
Cement grout with additive silica fume	4.34	10.06	2453	11.6	40.2	9.83
Cement grout with additive fly ash	2.90	7.94	2509	12.8	38.0	3.82

✓ Du Ting, Li Huiqiang. Mechanical properties of intensified recycled aggregate concrete[J]. China Concrete and Cement products, 2003(2): 19-20.

Chemical technology

Results of Experiment 2

Chemical grouts	Physical properties of recycled aggregates				Mechanical properties of recycled concrete	
	Water content /%	Water absorption rates /%	Apparent density /(kg/m^3)	Crushing index value /%	28d compressive strength (MPa)	Growth rate of strength /%
untreated	2.58	6.77	2470	16.73	30.78	0
Neat cement grout	3.37	6.93	2580	13.24	31.10	1.04
Cement grout with additive slag	3.78	7.51	2570	13.12	33.08	7.47
Cement grout with additive diatomite	2.71	7.13	2523	12.11	36.39	18.23
Cement grout with additive silica fume	2.79	7.43	2534	12.80	35.72	16.05
Polymer emulsion solution	2.63	6.34	2500	11.80	37.58	22.09

3. Acid solution

- Spray proper amount of acid solution, such as glacial acetic acid 冰醋酸or hydrochloric acid盐酸, on the surface of recycled aggregates, the acid will have chemical reaction with cement hydration products like $Ca(OH)_2$ and to form $CaCO_3$.

Experimental results of glacial acetic acid and hydrochloric acid

Aggregate types	Acid solution	28d compressive strength (MPa)		Concrete degrees	initial elastic modulus (10^3MPa)		Poisson's ratio
		cube	prism		Test value	Standard value	
Natural aggregates		26.3	17.8	C20	26.8	27.0	0.22
Recycled aggregates		24.3	16.5	C20	25.3	27.0	0.24
Recycled aggregates	glacial acetic acid	32.1	23.3	C25	33.0	29.5	0.18
Recycled aggregates	hydrochloric acid	27.3	20.0	C20	28.3	27.0	0.19

✓ Ismail S, Ramli M. Engineering properties of treated recycled concrete aggregate (RCA) for structural applications[J]. Construction and Building Materials, 2013, 44: 464-476.

4. Activator

- For modification of recycled aggregates, activators have similar function and mechanism to mixed cement grout. Immersing the recycled aggregates with inorganic composite alkaline activator and organic compound acid ester activator respectively, the test results are shown in table blow.

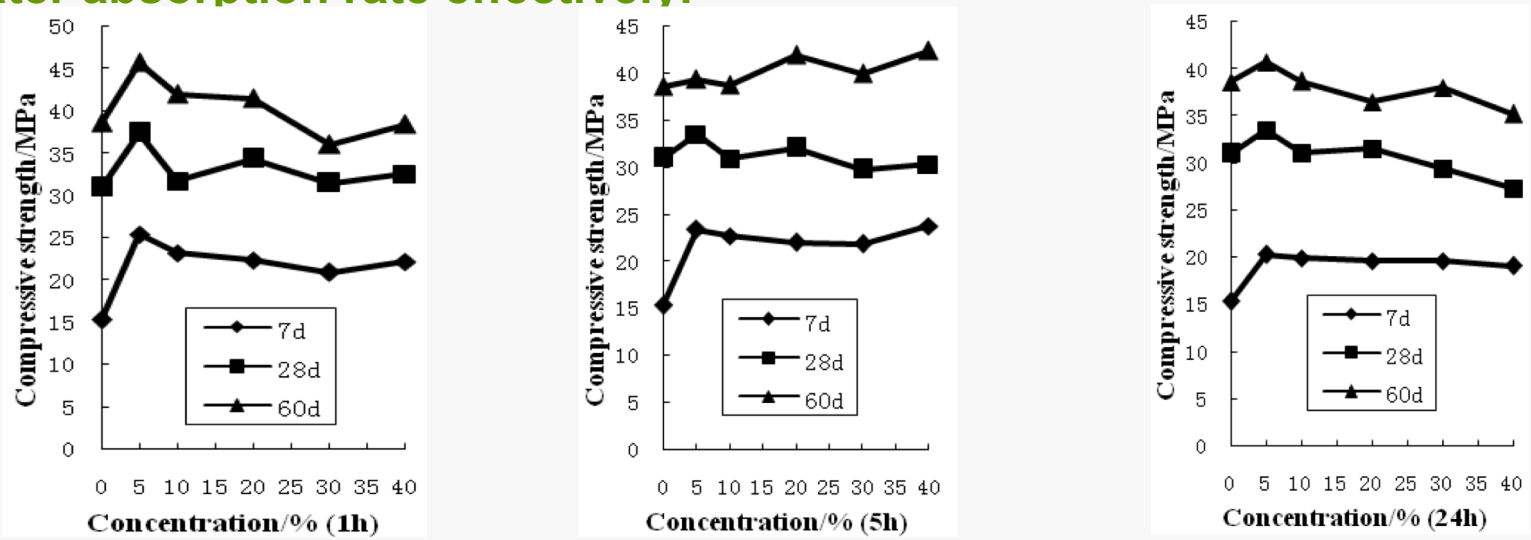
Comparisons of recycled aggregates' properties

Aggregates	Water absorption rates /%		Crushing index value /%	Apparent density /(kg/m³)
	10min	1h		
Untreated	3.80	6.25	24.1	2269
Inorganic impregnating solution	2.60	5.42	18.9	2290
Organic impregnating solution	3.50	5.73	22.5	2289

Wu Xuemei, Gao Yaobing, Yang Jiujun. Experiment of recycled concrete made of recycled aggregates modified by soaking method[J]. Henan Construction Material, 2009(1): 56-57.

5. Sodium silicate 硅酸钠

- **Sodium silicate solution will have chemical reaction with cement pastes of recycled aggregates, this will improve the bond behavior and density in the pores or cracks within the recycled aggregates, and also accelerate the cement setting, and reduce the recycled aggregates' water absorption rate effectively.**



Compressive strength of recycled concrete under different concentration and soaking time

Sata V, Wongsa A, Chindaprasirt P. Properties of pervious geopolymer concrete using recycled aggregates[J]. Construction & Building Materials, 2013, 42(9):33–39.

Chemical technology

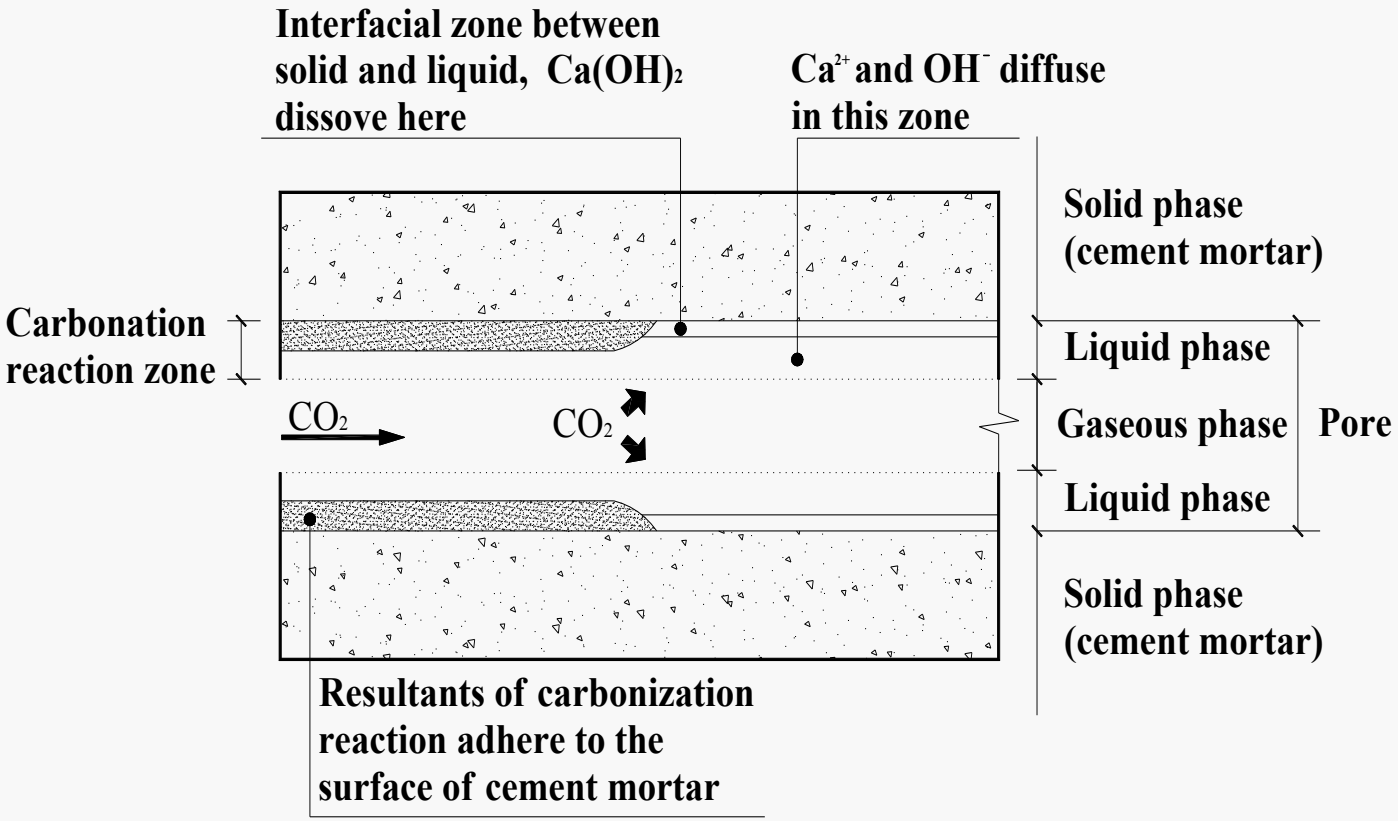
- **Summary of chemical technology**

  This technology uses chemical grout soaking to improve the performance of the adhering mortar in place of removing it. And this technology has the advantage of convenient production process. However, this technology is still in the evaluation and discussion without been applied to engineering practice because of:

  - The possible subsequent chemical reaction;
  - The influence on the ultimate concrete strength;
  - The long-term stability of durability.

Carbonation technology

- **Carbonation mechanism**



Schematic diagram of carbonation mechanism

✓ Carbon dioxide uptake in demolished and crushed concrete, published by Norwegian Building Research Institute, www.byggforsk.no, ISBN 82-536-0900-0.

Carbonation technology

The generalized chemical reaction formulas are listed blow:

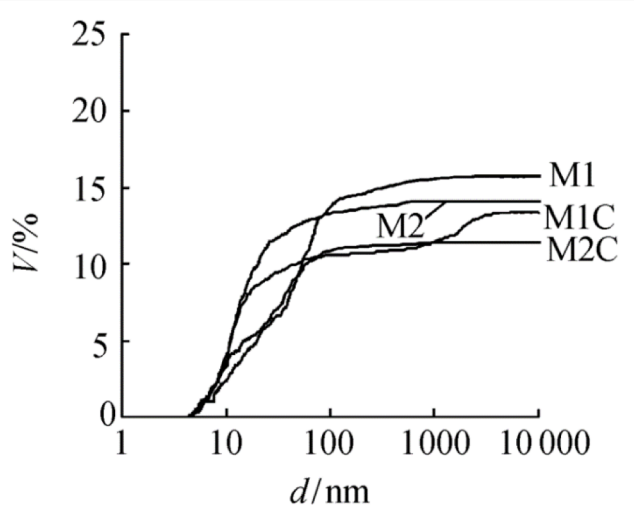
$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

$$3CaO \cdot 2SiO_2 \cdot 3H_2O + 3CO_2 \rightarrow 3CaCO_3 + 2SiO_2 + 3H_2O$$

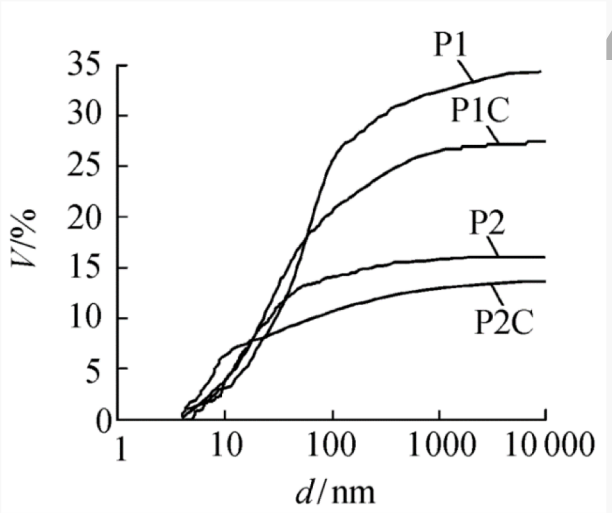
- When the $Ca(OH)_2$ is consumed, then the similar process will be followed by C-S-H($3CaO \cdot 2SiO_2 \cdot 3H_2O$) . In this transformation, water is needed while its amount seldom changes.
- Carbonation will contribute to volume change, normally because the precipitation of $CaCO_3$ mainly fill empty spaces in the capillary pores and cracks, thus leading to the reduction of porosity in the cement paste. Meanwhile, both the density and strength will be improved.

✓ Zhao Tiejun, Li Shujin. Effect of carbonation on permeability and porosity of concrete[J]. Industrial Construction, 2003(33): 46-48.

Carbonation technology



Effect of carbonation on porosity of cement mortar



Effect of carbonation on porosity of hardened cement paste

M1, M2, P1, P2 represent uncarbonated specimens, while M1C, M2C, P1C, P2C represent carbonated specimens. The cumulative porosity rates V/% of the hardened cement paste and cement mortar, before and after carbonation, changes according to pore diameters' variations.

FANG Yong-hao, ZHANG Y-itao, MO Xiang-yin, CHEN Yu-feng. Influence of carbonation on the microstructure and permeability of hardened cement paste and mortar[J]. Journal of Hohai University(Natural Sciences), 2005(1): 104-107.

Carbonation technology

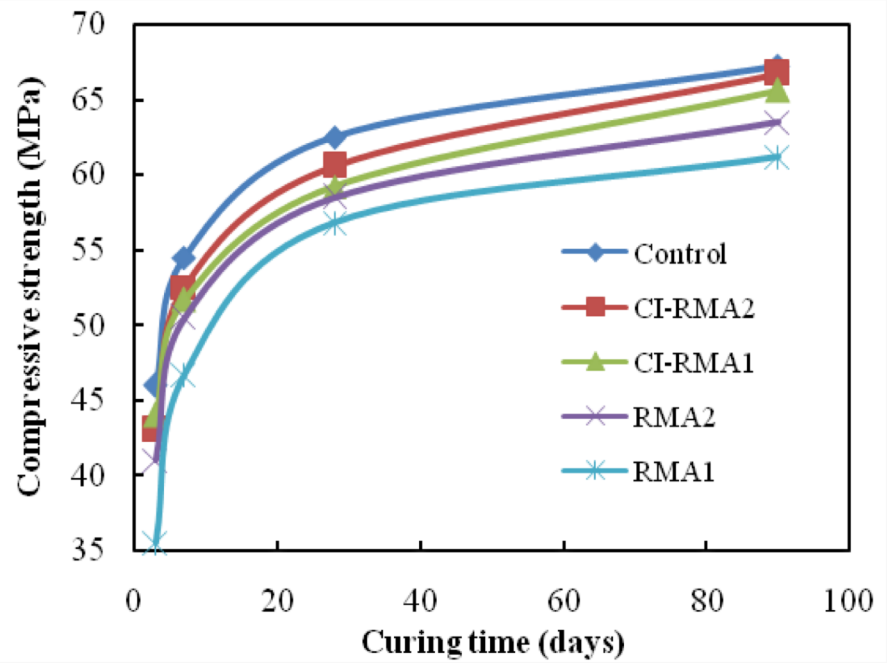
The other experiment chooses recycled mortar aggregates (RMA) to illustrate the relevant carbonation problems. RMA1 and RMA2，with sand to cement ratios of 3.0 and 2.5, and water to cement ratios of 0.55 and 0.45, respectively. And their carbonated counterparts are CI-RMA1 and CI-RMA2, respectively.

Physical properties of aggregates

Property	Particle size (mm)	Aggregate type				
		Natural granite	RMA1	RMA2	CI-RMA1	CI-RMA2
Density (Kg/m3)	20	2620	2326	2355	2345	2371
	10	2620	2326	2355	2351	2379
Water absorption (%)	20	0.89	11.82	9.30	7.32	4.84
	10	0.87	12.25	10.81	7.57	4.95
10% Fine value (KN)	14	156	96	116	108	134

✓ Baojian Zhan, Chi Sun Poon, Qiong Liu, Shi cong Kou, Caijun Shi. Experimental study on CO2 curing for enhancement of recycled aggregate properties. Construction and Building Materials: http://dx.doi.org/10.1016/j.conbuildmat.2013.09.008.

Carbonation technology



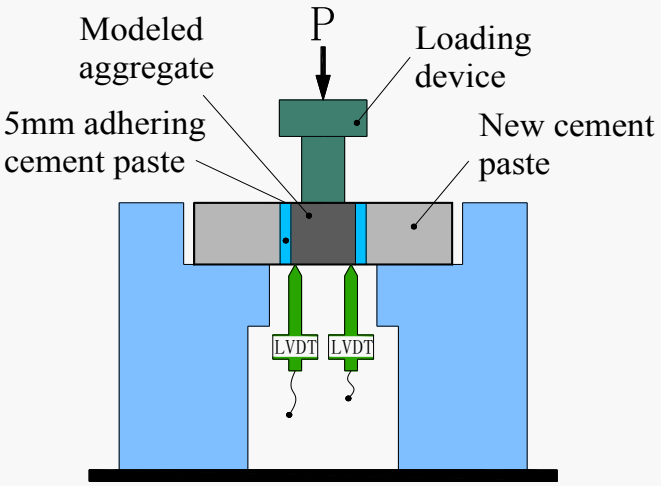
Development of compressive strength of concrete

Both the CI-RMA1 and CI-RMA2 improved the compressive strength of the concrete significantly. At 90 days, the compressive strength of concrete made with CI-RMA2 was only 1% lower than that of control concrete. Besides, there is also an improvement in the resistance to chloride ion penetration for the concrete prepared with CI-RMA, and the drying shrinkage was decreased.

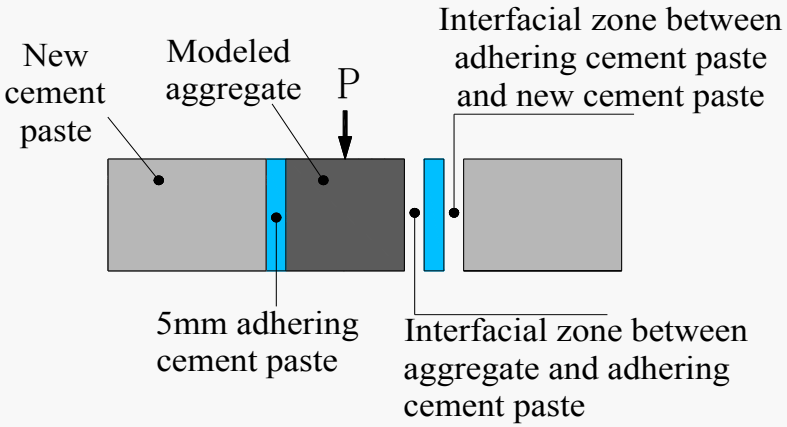
✓ **Kou Shi-Cong, Zhan Bao-jian, Poon Chi-Sun. Use of a CO2 curing step to improve the properties of concrete prepared with recycled aggregates[J]. Cement & Concrete Composites, 2014(45): 22-28.**

Carbonation technology

- **Push-out test of modeled recycled concrete**



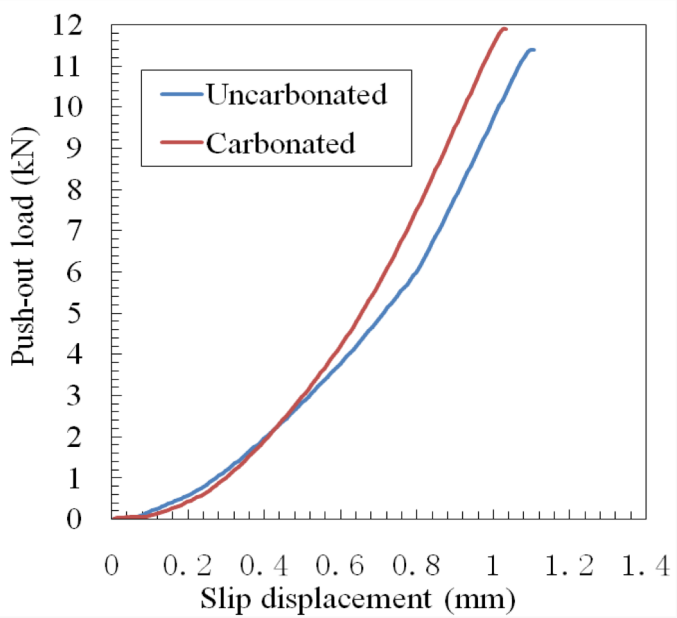
Test device



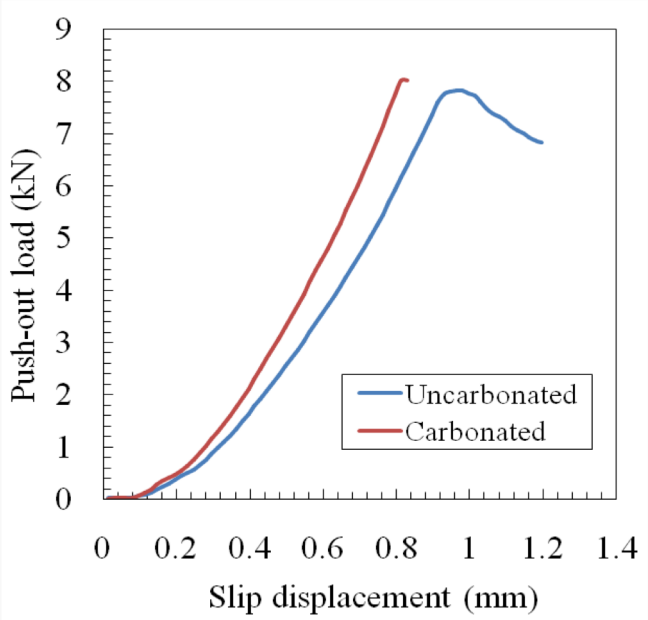
Schematic diagram of modeled recycled aggregate

Carbonation technology

- **Push-out test of modeled recycled concrete**



W/C of new and old cement paste is 0.45 and 0.37, respectively



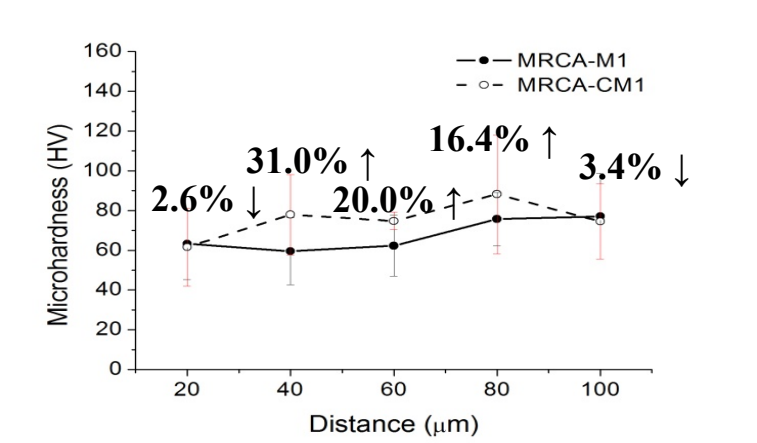
W/C of new and old cement paste is 0.45 and 0.68, respectively

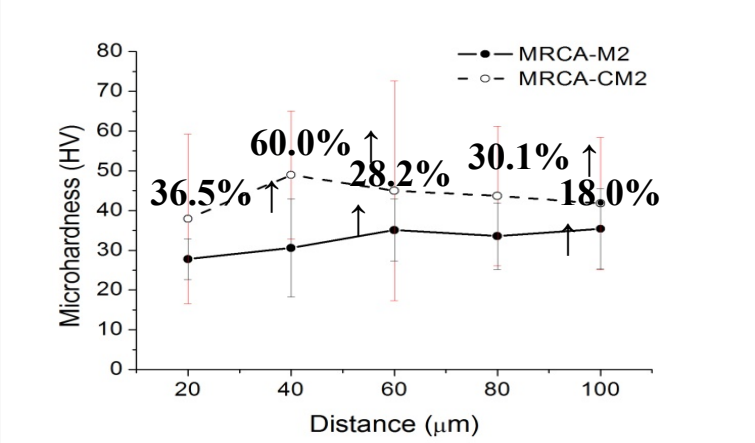
- With the increase of water cement ratio, the load will improve;
- Push-out load of carbonated is higher than uncarbonated;
- After carbonation, specimens' brittleness will improve.

- Chunhui Wang, **Jianzhuang Xiao**, Guanzhen Zhang, Long Li. Interfacial properties of modeled recycled aggregate concrete modified by carbonation. *Construction and Building Materials*, 2016, 105: 307-320.

Carbonation technology

Micro-hardness test on modeled recycled concrete

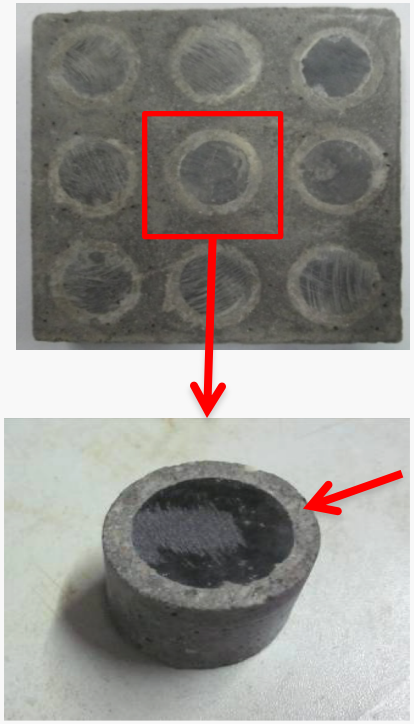


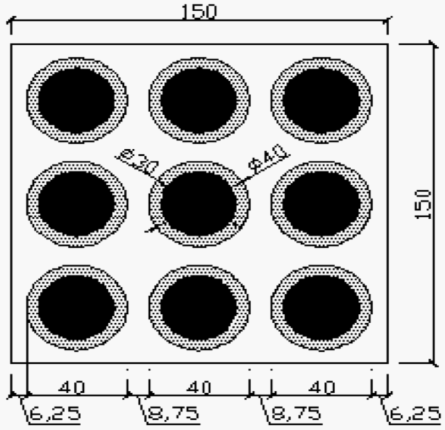


- **After carbonation, the hardness of ITZ and old mortar increased, especially the ITZ;**
- **With the increase of water cement ratio of old mortar, the strength of modeled recycled concrete aggregate was improved more significantly, the average gains are 12% and 35%.**

- Long Li, Jianzhuang Xiao, Chi Sun Poon. Compressive behavior of recycled aggregate concrete at high strain rates. *Materials and Structures*, 2016, 49(11): 4451–4462.

Carbonation technology





The preparation and performance test of modeled recycled concrete aggregate

Old mortar:

① M1(w/c=0.5)

② M2(w/c=0.6)

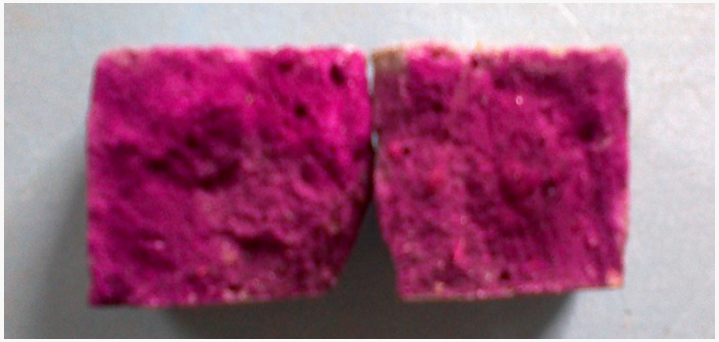
①	MRCA-M1
②	MRCA-M2
③	MRCA-CM1
④	MRCA-CM2

①	MRAC-M1
②	MRAC-M2
③	MRAC-CM1
④	MRAC-CM2

	MRCA-M1	MRCA-CM1	MRCA-M2	MRCA-CM2
Water absorption ratio	3.86%	3.16%	4.12%	3.67%

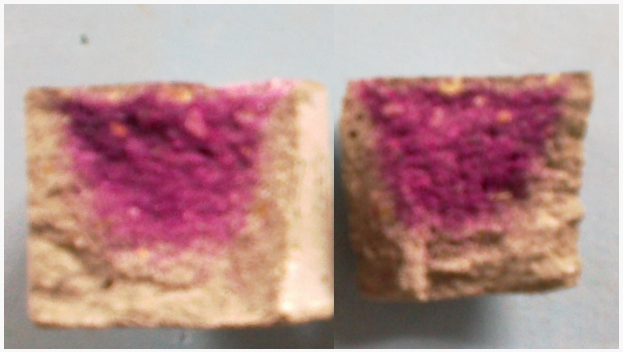
Carbonation technology

Carbonation of modeled recycled concrete aggregate

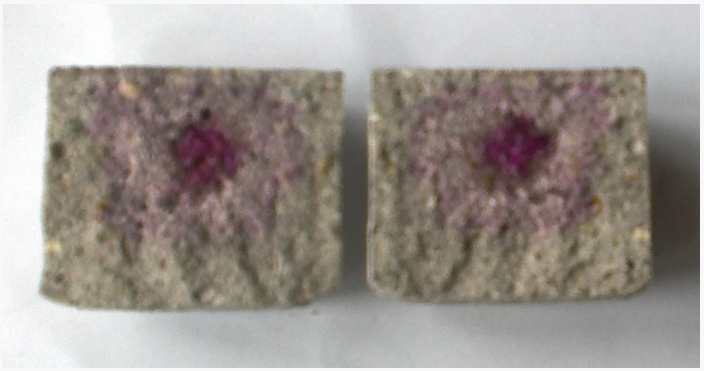


The carbonization age of 0 day

The carbonization age of 7 days



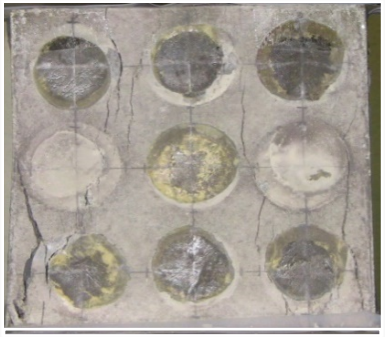
The carbonization age of 14 days



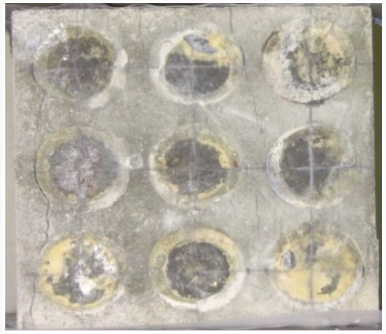
The carbonization age of 21 days

Carbonation technology

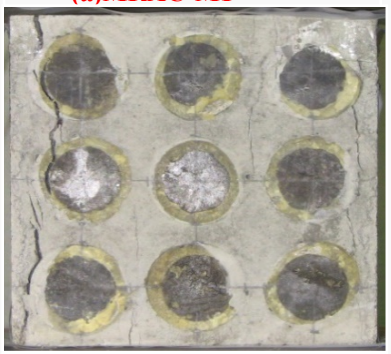
The effect of carbonation on modeled recycled concrete



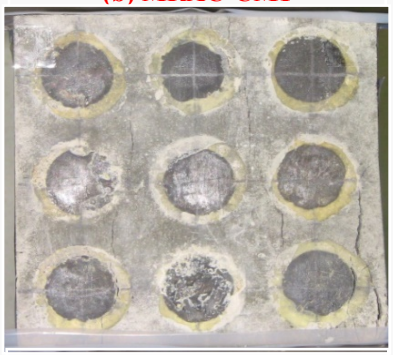
(a)MRAC-M1



(b) MRAC-CM1

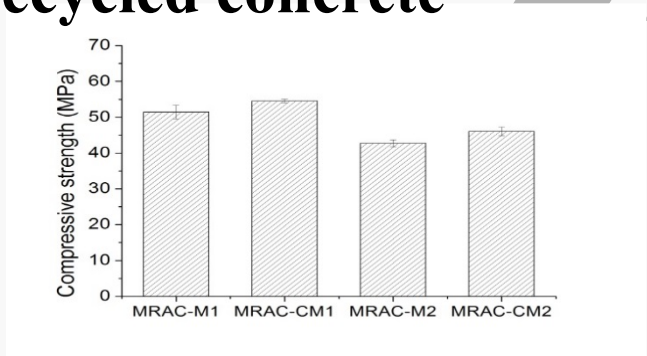


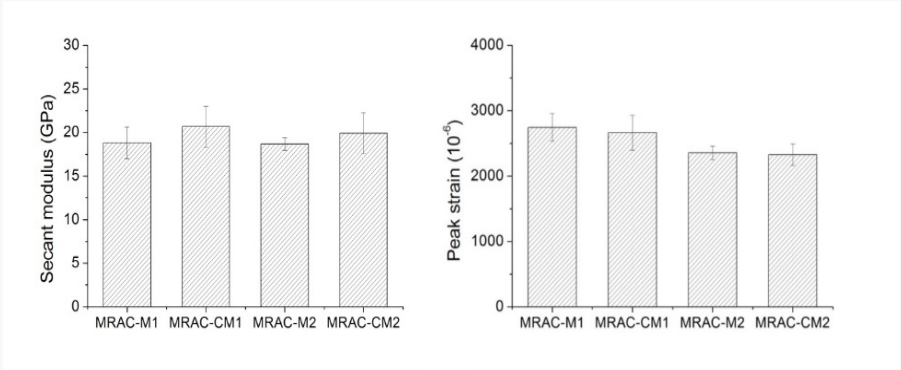
(c) MRAC-M2



(d) MRAC-CM2

- The recycled concrete after carbonization have more cracks in the new interface after failure



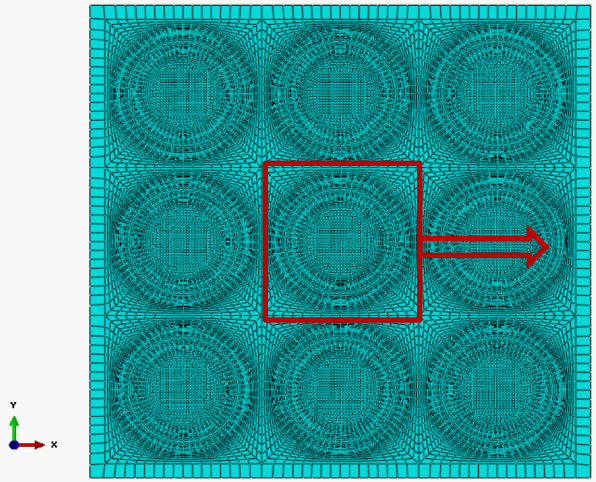


- Compressive strength increased;
- The elastic modulus increases and the peak strain decreases

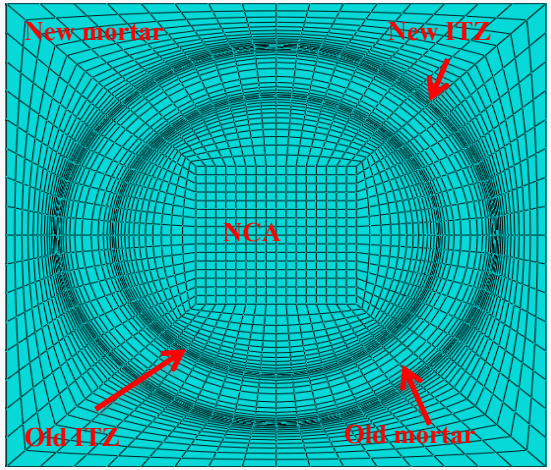
Carbonation technology

The simulation of carbonated modeled recycled concrete

By using the finite element model, the mechanical properties of the recycled aggregates after carbonization of the recycled aggregate were simulated.



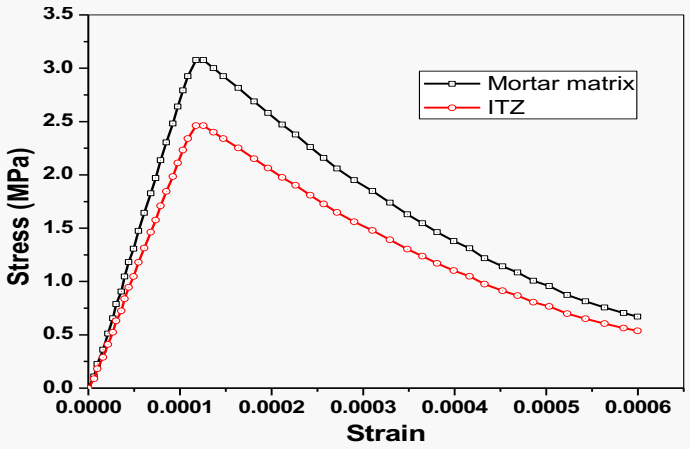
Global FEA model



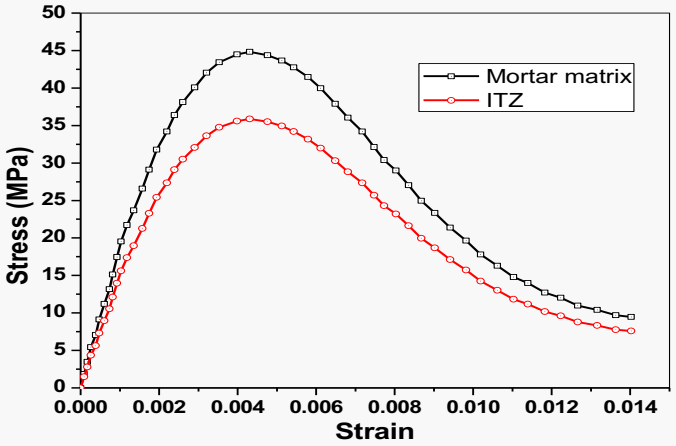
Details of each phase

Carbonation technology

Constitutive model



Tensile constitutive model



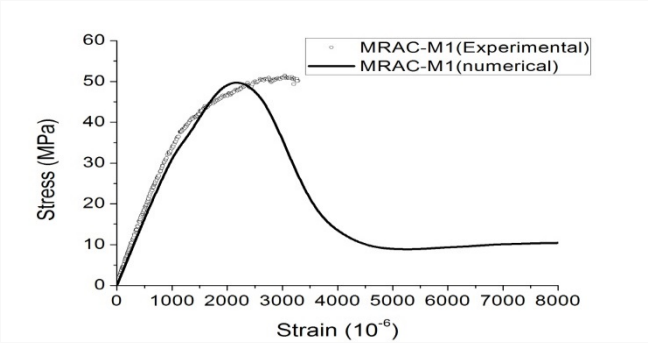
Compressive constitutive model

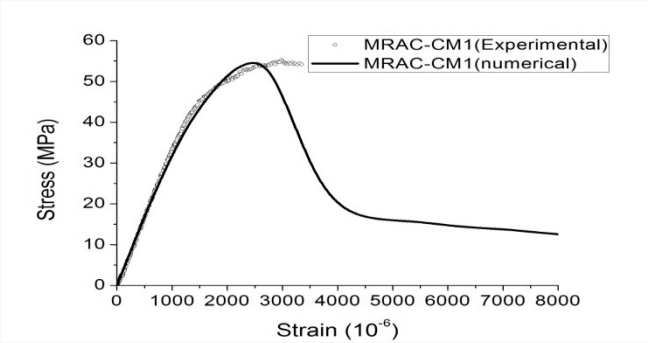
- Plastic damage constitutive model
- *fc*(ITZ)= 85%* *fc* (mortar)

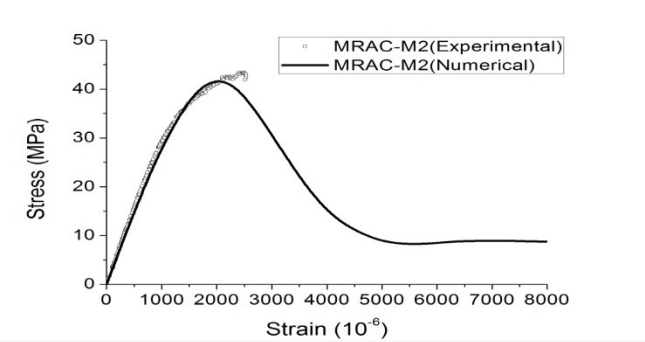
Carbonation technology

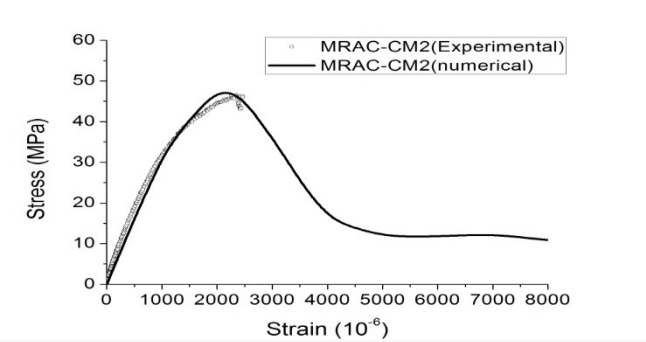
Simulation results

The strength of the old mortar and interfacial transition zone in the MRCA after carbonization is determined by the micro-hardness test results.









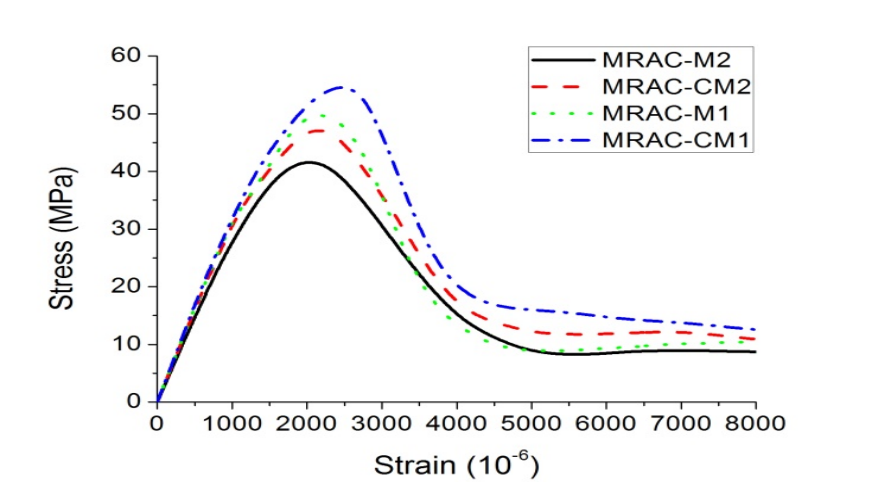
Carbonation technology

Simulation results

Number	Compressive strength			Elastic Modulus		
	Test results（MPa）	Simulation results（MPa）	Deviation（%）	Test results（GPa）	Simulation results（GPa）	Deviation（%）
MRAC-M1	51.4	50.0	2.72	33.8	33.0	2.4
MRAC-CM1	54.5	54.9	0.73	39.7	34.0	14.3
MRAC-M2	42.8	42.2	1.40	32.8	29.9	8.8
MRAC-CM2	46.1	47.3	2.60	33.4	32.4	3.0

Carbonation technology

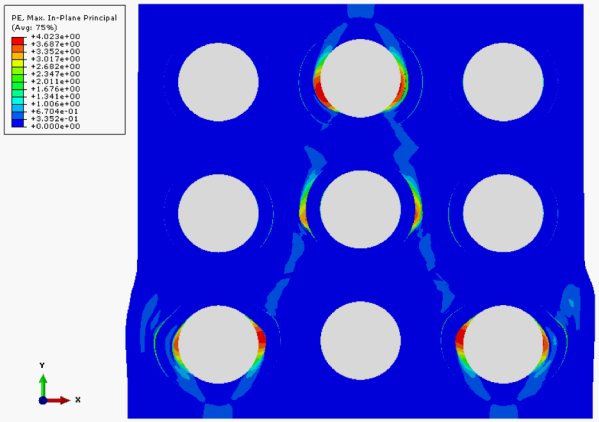
Simulation results of stress - strain curve



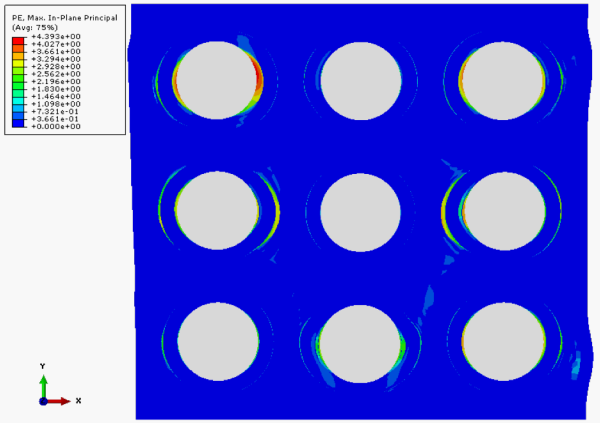
- **Carbonation of MRCA improves the compressive strength and modulus of elasticity of the MRAC while reducing the peak strain slightly.**

Carbonation technology

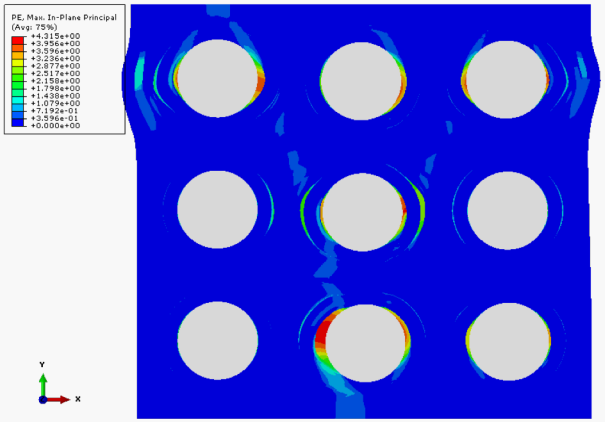
Failure mode



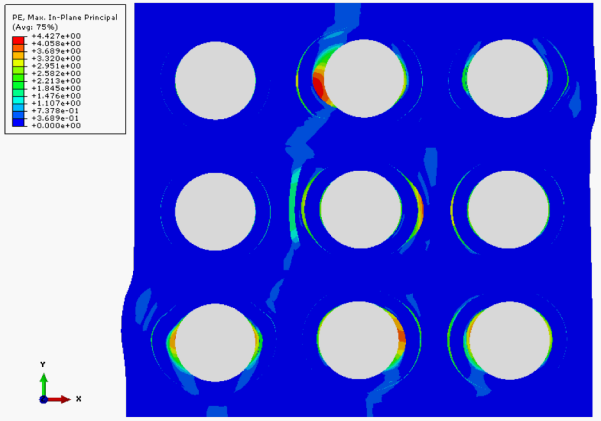
(a) MRAC-M1



(b) MRAC-CM1

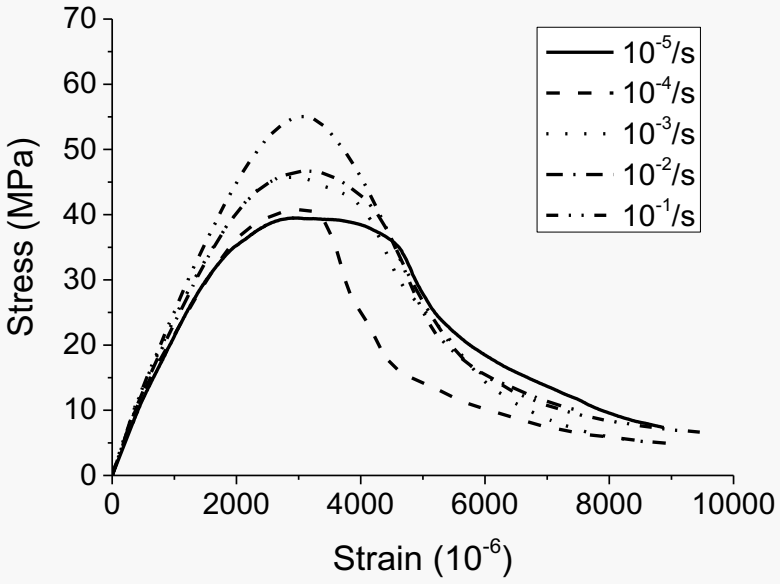


(c) MRAC-M2

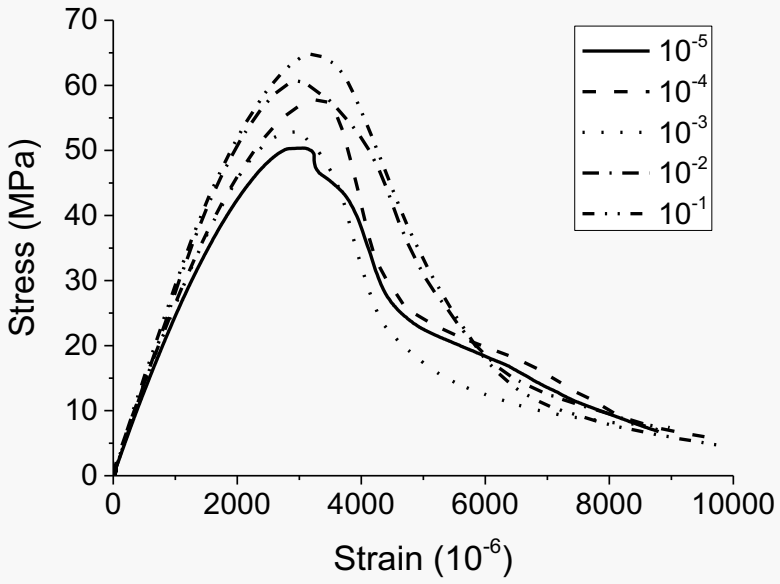


(d) MRAC-CM2

Dynamic performance



Typical stress-strain curves of RAC specimens at different strain rates



Typical stress-strain curves of CRAC specimens at different strain rates

Carbonation technology

- **Summary of carbonation technology**

  This technology has some commons with chemical technology based on the strengthening of cement pastes. Carbonization technology has the simple processes and environmental friendly advantages. However, there is a lot of subsequent research work to be done when considering the following problems:

  - The cost of industrial carbon dioxide collection
  - Carbonization curing room
  - The control of conditions such as pressure, temperature, humidity.

Conclusion

- From the aspects such as production, processing, mix proportion design, construction, structure, a comprehensive introduction was made on the modification of recycled aggregates and recycled concrete.
- The final purpose is to explore one of the best ways to make recycled aggregates meet the requirements on mechanical performance and durability performance of concrete, and can be applied to practical engineering.
- Although a lot of optimization methods were developed, there still exhibit some problems. If we can combine these optimization methods, maybe they can satisfy the requirement of engineering practice.
- In addition, we also need to consider environmental factors, resource consumption and economic costs and other issues, so it's necessary to conduct subsequent research.
- Modification investigation let us know more, then tailored recycled aggregate and recycled concrete can be achieved for better and more suitable application.

同济大学 TONGJI UNIVERSITY | 土木工程学院 COLLEGE OF CIVIL ENGINEERING

Acknowledgements

National Natural Science Foundation of China

(No: 51178340, 51325802)

Sino-Japan Research Cooperative Program sponsored by Ministry of Science and Technology in China (No: 2016YFE0118200)

Thank you for your kind comments!