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# Mechanical properties of pervious concrete with recycled aggregate

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**Abstract.** In order to research the influence of different recycled aggregate contents on the mechanical properties of pervious concrete, the experimental study and numerical simulation analysis of the mechanical properties of pervious concrete with five kinds of recycled aggregates contents (0%, 25%, 50%, 75% and 100%) are carried out in this paper. The experimental test were first performed on concrete specimens of different sizes in order to determine the influence of recycled aggregate on the compressive strength and splitting tensile strength, direct tension strength and bending strength. Then, the development of the internal cracks of pervious concrete under different working conditions is studied more intuitively by $PFC^{3D}$. The experimental results show that the concrete compressive strength, tensile strength and bending strength decrease with the increase of the recycled aggregate contents. This trend of reduction is not only related to the brittleness of recycled aggregate concrete, but also to the weak viscosity of recycled aggregate and cement paste. It is found that the fracture surface of pervious concrete with recycled aggregate is smoother than that of natural aggregate pervious concrete by $PFC^{3D}$, which means that the bridging effect is weakened in the stress transfer between the left and right sides of the crack. Through the analysis of the development of the internal cracks, the recycled aggregate concrete generated more cracks than the natural aggregate concrete, which means that the recycled aggregate concrete is easier to form a coalescence fracture surface and eventually break.

**Keywords:** recycled aggregate; content; pervious concrete; mechanical properties; numerical simulation by $PFC^{3D}$

## 1. Introduction

In recent years, many cities are facing the problem of old city reconstruction with the rapid development of economy and the rising of real estate. This will result in a large amount of construction waste, and if these concrete wastes are not disposed in time, they will seriously pollute the environment (Coelho and Brito 2011, Silva *et al.* 2015). The appearance of recycled aggregate alleviates this problem. Recycled aggregate refers to the crush of waste building concrete as a coarse aggregate of pervious concrete, partially or entirely replace the natural aggregate in order to achieve the purpose of cyclic utilization. Recycled aggregate (RA) instead of natural aggregate (NA) is considered as the most effective means to deal with construction waste in the field construction, which promotes the construction of sustainable development (Sagoe-Crentsil *et al.* 2001). Pervious concrete, as a kind of green environmental material (Sata *et al.* 2016), has many characteristics that ordinary concrete doesn't have, such as high permeability, less cement consumption and simple construction. And it has some applications in pervious pavement, hydraulic structure and ecological slope protection.

Compared with natural aggregate concrete (NAC), the reduction or enhancement of the strength of recycled aggregate concrete (RAC) has been studied in many previous literatures (Kou 2010, Wagih *et al.* 2013, Carneiro *et al.* 2014). In general, the mechanical properties of RAC are lower than those of NAC, and this decrease is proportional to the replacement amount of RA (Rahal 2007, Tabsh and Abdelfatah 2009). In addition, the weakening trend will be intensified when the water-cement ratio is relatively low (Rao *et al.* 2007, Choi and Yun 2012). Many researchers have made a lot of experiments on the theory of strength reduction of RAC (Liang *et al.* 2017). It is considered that the strength value of concrete decreases by about 15~35% due to the addition of RA (González *et al.* 2002). Ghorbel *et al.* (2017) has proved that the tensile strength and modulus of elasticity of concrete reduce in varying degrees by RA instead of NA. He considers that this is mainly due to the higher porosity of RAC, and the worse adhesion between RA and cement paste. Rao's research results also show that the degradation of concrete strength depends on the replacement ratio and aggregate particle size, which in his opinion is mainly due to the greater water absorption of RA than NA (Rao *et al.* 2007). Abdollahzadeh *et al.* (2016) held that the use of recycled aggregate (RA) decreases the compressive strength, modulus of elasticity and resistance to freezing and thawing of concrete compared to those of natural aggregate concrete. However, some scholars have indicated that the strength of concrete mixed with RA is close to that of NAC (or even higher) (Malešev *et al.* 2010, Razaqpur *et al.* 2010, Younis *et al.* 2013). Xiao *et al.* (2004) have studied the use of RA by 30% to 100% and the results showed that when the replacement amount of RA is 30%, the reduction in

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compressive strength of concrete can be neglected. The results of Wagih *et al*. (2013) show that the optimal replacement rate of RA is between 25%~50%. However, Carneiro *et al.* (2014) deemed that concrete with 25% of RA has a greater strength in comparison with concrete containing NA, and the increment in the strength of concrete with these aggregates is due to the fracture of RA in concrete. Gomez-Soberón (2002) has explained the reasons for the above conclusions. He thinks that the ultimate strength of RA is affected by the quality of the waste concrete. Therefore, Tavakoli and Soroushian (1996) has been further studied that the strength of RAC was affected by the main factors of original concrete, such as the influence of the original concrete strength, the ratio of coarse aggregate to fine aggregate and the ratio of the maximum particle size of NA to that of RAC.

The above studies show that the influence of RA on the mechanical properties of concrete is uncertain. Most of previous studies focus on the mechanical properties of ordinary concrete (Chen *et al.* 2014, Chen and Bu 2016), and the research in the influence of RA on the mechanical properties of pervious concrete are limited. Therefore, the purpose of this study is to analyze the influence of RA from the local on the mechanical properties of pervious concrete, and determine whether pervious concrete with the RA can meet the requirements of field use. Then the development of internal cracks in concrete under various working conditions is simulated by PFC5.0, and the influence of RA on the mechanical properties of pervious concrete is analyzed intuitively, which provides theoretical support for the experiment.

## 2. Experimental detail

### 2.1 Mix proportions

CEM I 32.5R Portland cement with specific gravity of 3.15 g/cm$^3$ was used to cast the pervious concretes, and the compressive strength of the standard cube is 32.5 MPa after curing for 28d. The particle size range of NA used is 0~15 mm, and the particle size range of RA is 10~15 mm. In order to prevent the influence of the surface attachment of aggregates on the experimental results, the specimens were washed with clean water before carrying out the tests and then dried them to reach saturated dry condition. The main physical properties of NA and RA are given in Table 1.

The water-cement ratio of the experimental design is 0.258 by the weight and 3.920 by the volume. The amount of cement and water remained unchanged, which are 400kg/m$^3$ and 103 kg/m$^3$, respectively. In view of the above factors, five kinds of concrete samples were poured in this study. They are denoted as NAC, RAC25, RAC50, RAC75 and RAC100 respectively, and the recycled aggregates account for 0%, 25%, 50%, 75% and 100% of the total volume of coarse aggregates, respectively. The materials and dosage of each sample are shown in Table 2.

Table 1 Physical properties of aggregates used in experiments

| Type | Density (kg/m$^3$) | Water absorption (%) | Crushing value (%) |
|---|---|---|---|
| NA | 2652 | 1.32 | 4.00 |
| RA | 2633 | 3.25 | 13.42 |

Table 2 The mixture proportion of materials used in the experiments (kg/m$^3$)

| Mix ID | Material consumption | | | | Plasticizer |
|---|---|---|---|---|---|
| | Cement | Water | NA | RA | |
| NAC | 400 | 103 | 1425 | 0 | 1.485 |
| RAC25 | 400 | 103 | 1068.75 | 356.25 | 1.485 |
| RAC50 | 400 | 103 | 712.5 | 712.5 | 1.700 |
| RAC75 | 400 | 103 | 356.25 | 1068.75 | 1.800 |
| RAC100 | 400 | 103 | 0 | 1425 | 2.100 |

Concrete is casted into molds of 150 mm×150 mm×150 mm and 100 mm×100 mm×400 mm, and then demolding is taken after 24h. Next the specimens are put into the water curing for 28d, and the corresponding mechanics experiment is carried out.

### 2.2 Concrete specimens

The uniaxial compression and splitting tension test were performed on 150mm×150mm×150 mm cube specimens in order to obtain the compressive strength and splitting tensile strength of pervious concrete with different recycled aggregate content. The tensile strengths were obtained by direct tension test conducted on 100mm×100mm×200mm cuboid specimens. The three-point bending and four-point bending tests were carried out on 100mm×100mm×400mm cuboid specimens to determine the bending strength . Three specimens are prepared for each test, and the average value is calculated for strength. The concrete specimens used in the experiment were maintained in water at least 28d before testing.

### 2.3 Test methods

The compressive strength of pervious concrete is obtained by uniaxial compression test on SANS test machine. Splitting tensile strength, three point bending tensile and four point bending tensile strength are obtained on SNT4605 microcomputer controlled electro-hydraulic servo universal testing machine. Although both splitting tensile and bending tests are performed on the same test machine, their test methods are quite different. Splitting tensile test is to place an iron bar between the specimen and the press to test the splitting tensile strength, as shown in Fig. 1(a), and the bending tensile test is to test the bending tensile strength of concrete specimens by modifying the pressure test machine, as shown in Fig. 1(b). It is difficult to stretch concrete specimen directly, so the steel discs were pasted on the two ends of the specimen by the structural adhesive. Thus, the specimen and the steel discs become integrated; the specimen and the test machine were connected together by the spherical joint system. The spherical joint can also automatically adjust the specimen position to reduce the eccentricity (Chen *et al.* 2017). An


(a) (b) (c)

Fig. 1 Test methods under different loading conditions

Table 3 Test results of mechanical properties for recycled aggregate pervious concrete

| Mix ID | Compressive strength (MPa) | Splitting tensile strength(MPa) | Three-point bending strength (MPa) | Four-point bending strength (MPa) | Direct tensile strength (MPa) |
|---|---|---|---|---|---|
| NAC | 44.996 | 2.382 | 3.337 | 2.949 | 2.301 |
| RAC25 | 32.723 | 2.062 | 2.722 | 2.239 | 2.250 |
| RAC50 | 29.861 | 1.936 | 2.337 | 1.898 | 2.131 |
| RAC75 | 21.365 | 1.775 | 1.946 | 1.801 | 1.400 |
| RAC100 | 15.324 | 1.373 | 1.231 | 1.109 | 1.201 |

anchor rod in the spherical joint system was connected with the fixture of MTS machine and the direct tensile test was carried out, as shown in Fig. 1(c).

## 3. Experimental results and analysis

According to the above test methods, the mechanical properties of concrete specimens with different recycled aggregate content are tested, and the mechanical properties are obtained, as shown in Table 3.

### *3.1 Compressive behavior*

An obvious weakening effect of recycled aggregate content on the compressive strength of the pervious concrete can be seen in Fig. 2. When the coarse aggregate is NA, the compressive strength of concrete reaches the maximum value of 44.996MPa. Hereafter, the compressive strength gradually decreases with the increase of recycled aggregate content. When the recycled aggregate content reaches 25%, the decrease rate of compressive strength tends to be small, but when it reaches 50%, the decrease rate of compressive strength increases again. There are two main reasons for the decrease of compressive strength of concrete. First of all, since the water absorption of RA is larger than NA, a large amount of water will be absorbed by RA to lower the water-cement ratio of concrete with the increase of recycled aggregate content, resulting in incomplete hydration of cement and indirectly reducing the compressive strength of concrete. Secondly, the strength of

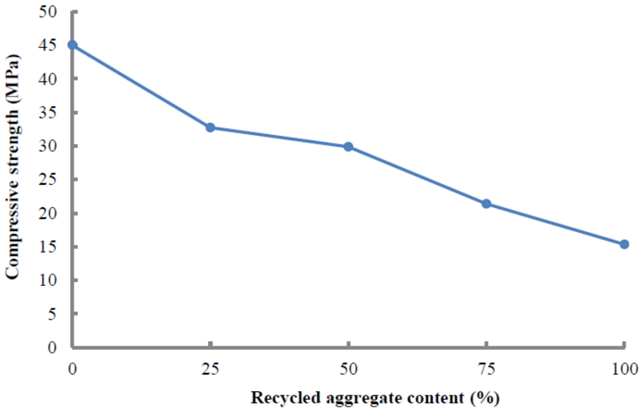



Fig. 2 Influence of recycled aggregate content on compressive strength of pervious concrete

Fig. 3 Failure of pervious concrete specimen under uniaxial compression

RA is relatively lower than that of NA, about 10~20MPa, and its porosity is high, which will cause stress concentration when being subjected to axial pressure and

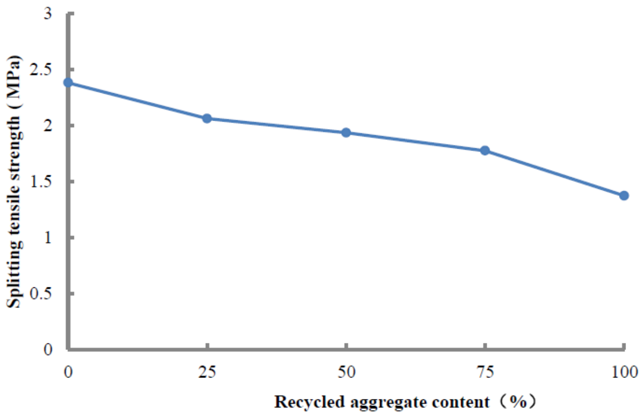



Fig. 4 Influence of recycled aggregate content on splitting tensile strength of pervious concrete

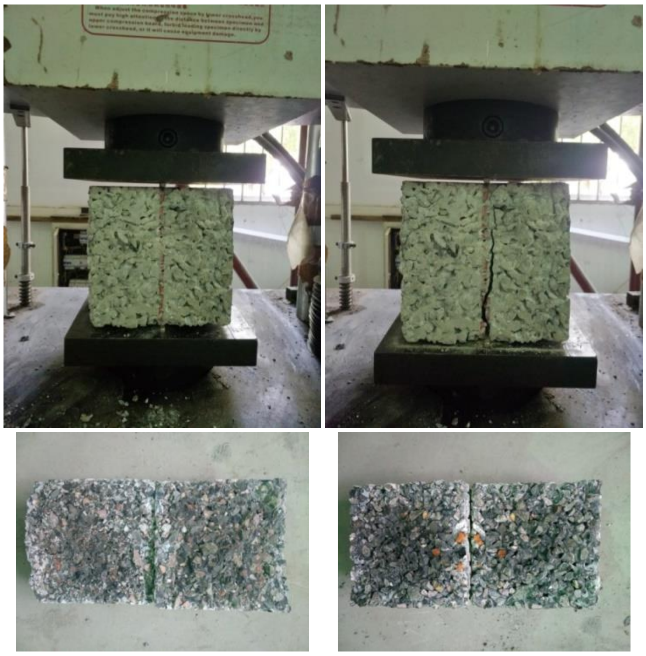
will have a negative effect on the compressive strength of concrete (Fig. 3). Therefore, the compressive strength of concrete will be further reduced with the increase of recycled aggregate content. Because the normal compressive strength of pervious concrete ranges from 5 to 20MPa, and the experimental results show that although the compressive strength decreases with the use of recycled aggregates, the concrete with RA is in the range of normal compressive strength and can be used normally in the application areas that do not require high strength pervious concrete, such as pavement.

### 3.2 Splitting tensile behavior

It can be seen in Fig. 4 that the splitting tensile strength of concrete specimens shows an obvious downward trend with the increase of recycled aggregate content. Compared with NAC, the splitting tensile strength of concrete decreases from 2.382 MPa to 1.373 MPa when the recycled aggregate content reaches 100% (the splitting strength loss is 42%). The main reason is that the porosity of pervious concrete is increasing with the increase of recycled aggregate content, and compared with NA, the bonding effect between RA and cement paste is weaker, which leads to a decrease trend in splitting strength. By observing the splitting tensile failure of concrete (as shown in Fig. 5), we can get that the splitting tensile failure surface will develop along the interface transition zone (ITZ) when the coarse aggregate is NA, and the splitting tensile failure surface will pass through the recycled aggregate when a part of NA is replaced by RA.

### 3.3 Bending tensile behavior

The effect of different recycled aggregate content on the three-point and four-point bending strength is shown in Fig 6. The bending strength is decreasing with the increase of recycled aggregate content. Compared with NAC, when the recycled aggregate content reaches 100%, the three-point bending strength decreases from 3.34MPa to 1.23MPa (strength loss is 63.2%), and the four-point bending strength decreases from 2.95MPa to 1.10MPa (strength loss is 62.7%).



NAC RAC100

Fig. 5 Failure of pervious concrete specimen under splitting tensile test

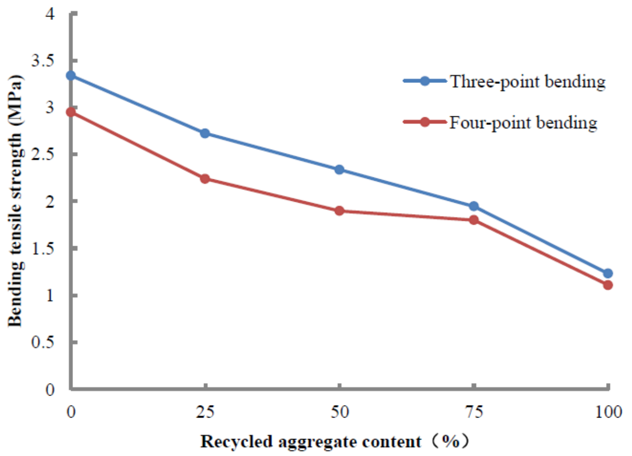



Fig. 6 Influence of recycled aggregate content on bending tensile strength of pervious concrete

The experimental results show that recycled aggregate content has a negative correlation with the bending strength of the pervious concrete. This is mainly due to the fact that the strength of the recycled aggregates themselves is lower than that of the natural aggregates and that the adhesion between the grout and the recycled aggregates is weaker, which results in the decrease of the bending strength with the increase of recycled aggregate content. As is shown in Fig. 7, the bending tensile fracture surface is similar to that of splitting tensile, and pervious concrete will show obvious brittleness when RA instead of a part of NA.

### 3.4 Direct tensile behavior

The tensile strength of pervious concrete with different recycled aggregate content is monitored by the MTS test

NAC RAC100

Fig. 7 Failure of pervious concrete specimen under splitting tensile test

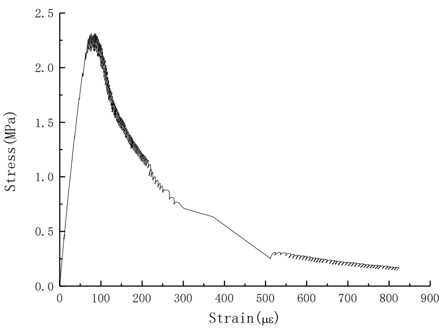
machine (as shown in Fig. 9). Through the analysis of the experimental data, the peak stress of tensile strength decreases with the increase of the recycled aggregate content. The strength loss is relatively small when the recycled aggregate content is less than 50%, but the strength loss decreases sharply when the recycled aggregate content is 75%. Compared with NAC, the strength loss is 42% (see Fig. 8). The experimental results show that the tensile strength of pervious concrete exhibits a significant downward trend with the use of RA, and the greater the content of recycled aggregate is, the faster the tensile strength decreases. Meanwhile, the elastic modulus of concrete also shows a downward trend. It can be seen that the RA instead of NA will result in the reduction of a series of mechanical properties of concrete, including tensile strength and elastic modulus.

## 4. Numerical simulation

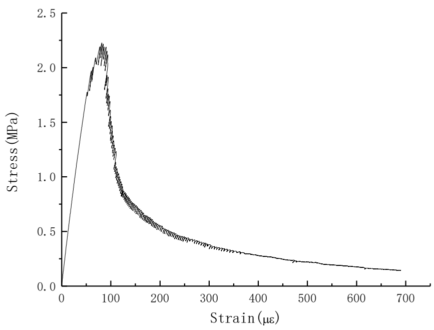
In order to more intuitively analyze the effect of recycled aggregate on the mechanical properties of pervious concrete, and to provide theoretical foundation for the experiment, $PFC^{3D}$ discrete element software is used to simulate the fracture condition of pervious concrete under various loading conditions in this paper. The influence of recycled aggregate on the mechanical properties of pervious concrete is further explored by analyzing and observing the development of internal cracks in pervious concrete.

### *4.1 Parameters*

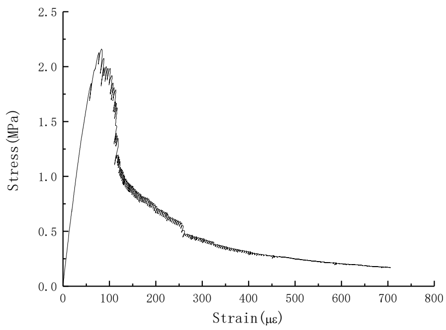
In the discrete element, any structure and object are composed of particles, and the interaction between particles determines the macroscopic mechanical properties of the object. For pervious concrete, the macro mechanical properties such as compressive strength, tensile strength, bending tensile strength and splitting tensile strength are determined by the interaction between particles. However, the mesoscopic parameters between particles can't be



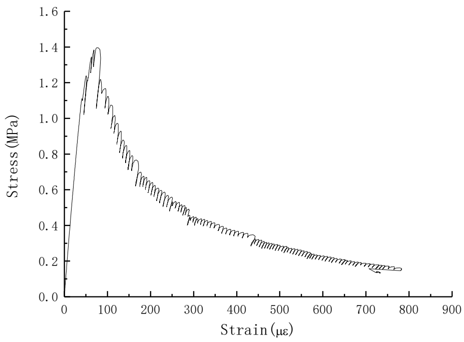

(a) NAC



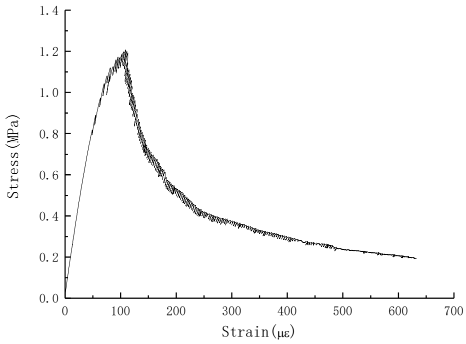

(b) RAC25




(c) RAC50




(d) RAC75




(e) RAC100

Fig. 8 Stress-strain curves of pervious concrete under direct tension

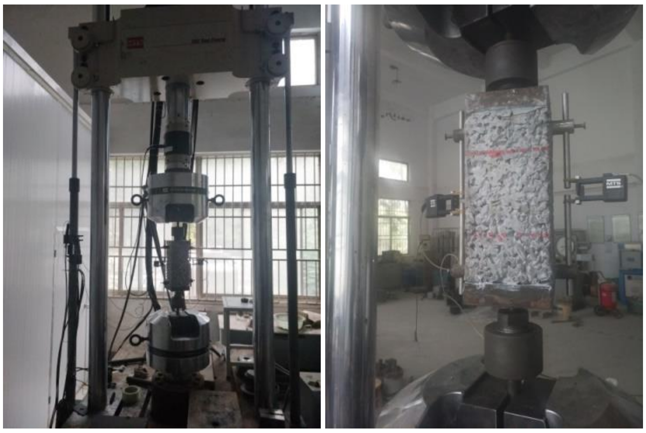


Fig. 9 Direct tensile test of pervious concrete with MTS test machine

Table 4 Mesoscopic parameters of the numerical model

| Micro-parameters of particles | | | Parallel bond model | |
|---|---|---|---|---|
| Parameters | NA | RA | Parameters | Values |
| Radius (mm) | 5~10 | 10~15 | Effective modulus of elasticity (Pa) | $9.38\times10^{9}$ |
| Density (kg/m$^3$) | 2550 | 2240 | Tensile strength (Pa) | $4.35\times10^{6}$ |
| Normal stiffness $k_n$ (N/m$^3$) | $4.0\times10^{10}$ | $3.5\times10^{10}$ | Cohesion (Pa) | $7\times10^{6}$ |
| $k_n/k_s$ | 1 | 1 | Bond radius (mm) | 0.5 |

obtained through laboratory tests and other macro mechanical tests. The calibration parameters of PFC calculation models are obtained through the best fitting of the stress-strain curves and the strength of the relevant to the experimental results. In this sense, the best fitting of stress-strain curve is reached through a heuristic technique based on the visual evaluation of the consistency between experimental results and numerical results (Pieralisi 2016). The mesoscopic parameters of the numerical model are showed in Table 4.

After determining the mesoscopic parameters of the model, the numerical simulation is carried out, and the numerical simulation results are analyzed. Finally, the results are compared with the experimental results.

### *4.2 Compressive behavior*

According to the above compressive test on pervious concrete, in order to be consistent with the experiment, the PFC model size is 150 mm×150 mm×150 mm, and the recycled aggregate content is 0%, 25%, 50%, 75% and 100%, respectively, simulating the compressive failure of concrete under different content. There are two loading plates on the top and bottom of the model, and the loading is controlled by displacement. The velocity of the top plate displacement is $1.67\times10^{-6}$ m/s (0.1 mm/min), which is consistent with the loading rate of the experiment. The PFC$^{3D}$ compression calculation model is shown in Fig. 10.

The compression calculation and analysis are carried out on the pervious concrete with five kinds of recycled aggregate contents, and the development of the internal

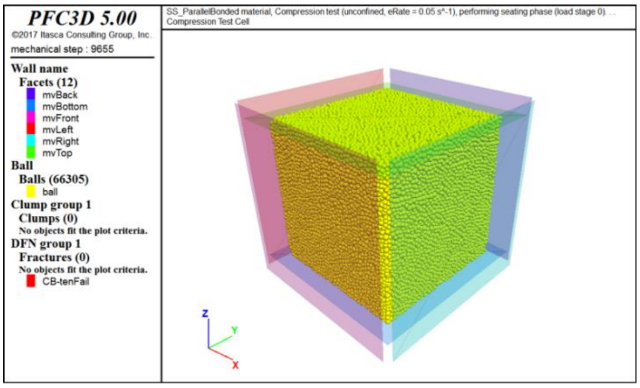


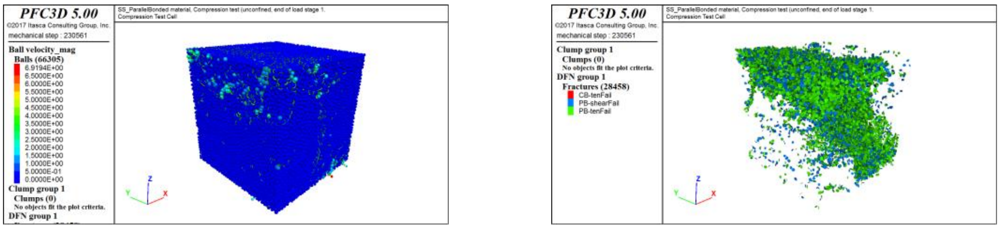

Fig. 10 PFC$^{3D}$ calculation model for compression

fissure of the concrete with various contents is shown in Fig. 11.

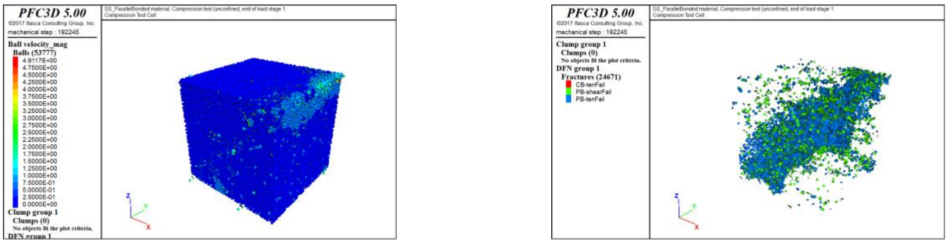
According to the fracture development in Fig. 11, when the aggregate is NA, the generation of internal crack is mainly caused by tensile failure, and the effect of shear failure is weak. With the increase of recycled aggregate contents, the effect of shear failure is strengthened. This is mainly due to the strong bonding effect between NA and cement paste, and shear failure is not easy to destroy this bonding effect. Finally, tensile failure occurs after reaching ultimate tensile strength. However, the bonding between RA and cement paste is weak, and relative slip easily occurs, resulting in shear failure. And with the increase of the recycled aggregate content, the internal cracks in the concrete increase gradually, and the compressive strength gradually decreases. Because the concrete with the recycled aggregates is relatively large in porosity, which can easily cause stress concentration in the hole wall and leads to premature damage of the material. Continued loading will form a continuous fracture surface, resulting in the final destruction of the pervious concrete. The relationship between the recycled aggregate content and compressive strength of pervious concrete is shown in Fig. 12. With the increase of recycled aggregate content, the compressive strength and elastic modulus of pervious concrete decrease correspondingly, and the simulation results are consistent with the experimental research conclusions.

### *4.3 Splitting tensile behavior*

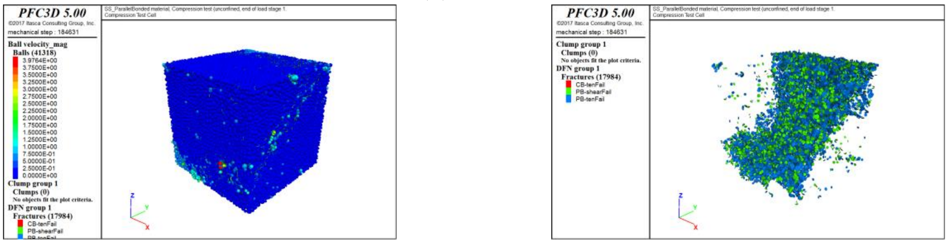
The relationship between the recycled aggregate content and the splitting tensile strength obtained by numerical simulation is presented in Fig. 13(a). The splitting tensile strength of the models ranges from 1.123 MPa to 2.393 MPa, decreasing with the recycled aggregate content. A comparison between the numerical and experimental results of splitting tensile strength depending on the recycled aggregate content is given in Fig. 13(b). The results show that the strength range and the downward trend of the numerical simulation coincide with the experimental results. This anastomosis shows that the meso-cracks obtained by splitting model reproduce the damage of pervious concrete under the influence of recycled aggregate content.



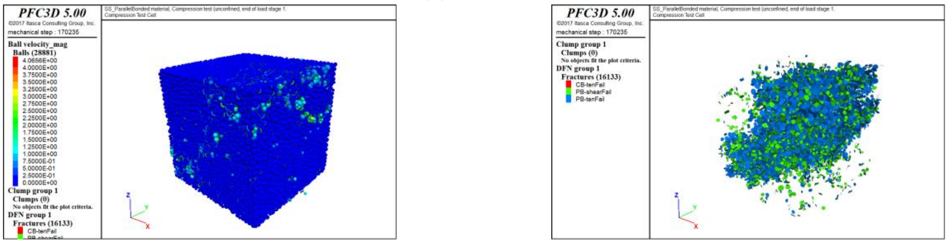

(a) NAC



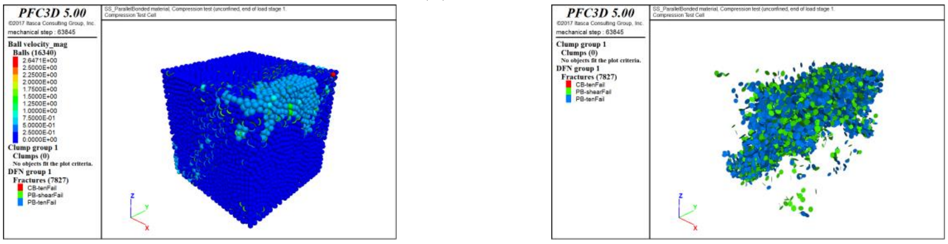

(b) RAC25




(c) RAC50




(d) RAC75




(e) RAC100

Fig. 11 Fracture development of pervious concrete with different content under uniaxial compression

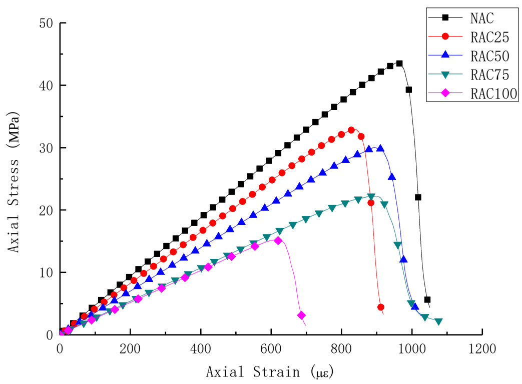
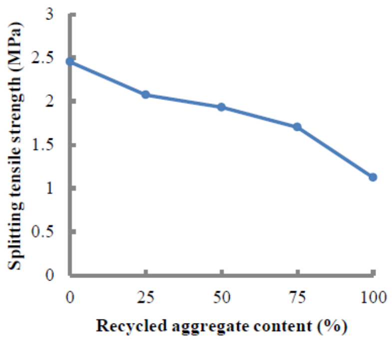
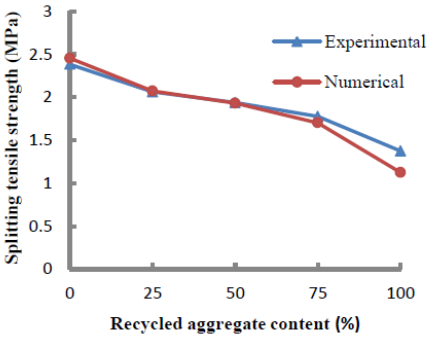



Fig. 12 Numerical data for compressive stress-strain response




(a)

Fig. 13 Numerical and experimental splitting tensile strength depending on the recycled aggregate content

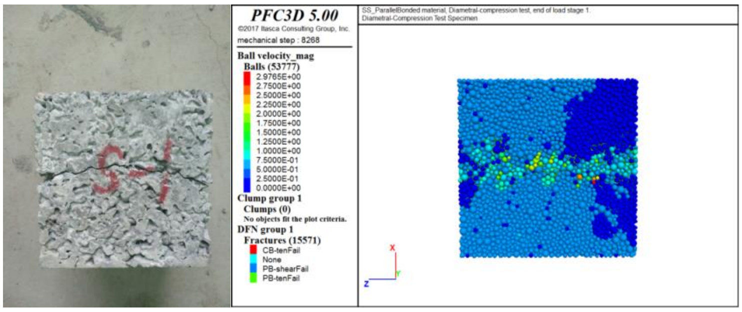



(b)

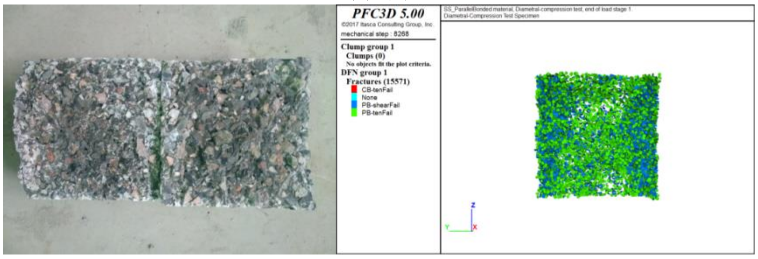
Fig. 13 Continued

Fig. 14 presents a more phenomenal comparison between the damage morphology of the specimen and the formation of the internal fissure in the corresponding numerical simulation. Fig. 14(a) shows the rupture form observed on the top of the concrete specimens of pervious concrete with 0% of the recycled aggregate content. The typical failure surface on the top of the concrete specimen after splitting failure by PFC simulation is similar to that of the test specimen, as shown in Fig. 14(b).

In the experiment, the crack first occurs in the contact area between the loading area and the specimen surface, and then develops gradually towards the test specimen along

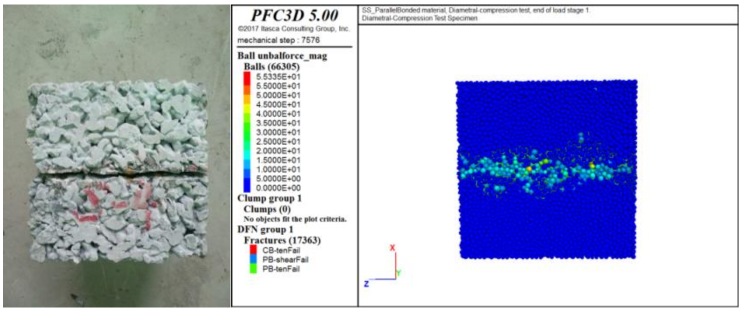



(a) (b)

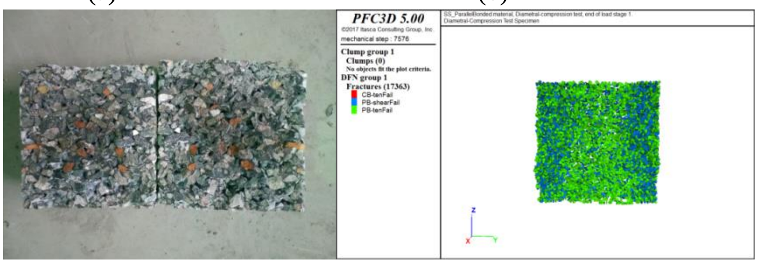



(c)(d)

Fig. 14 Experimental and numerical typical fracture surface development in specimens with 0% of recycled aggregate content (NAC)

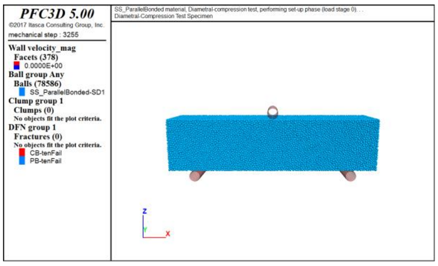



(a) (b)

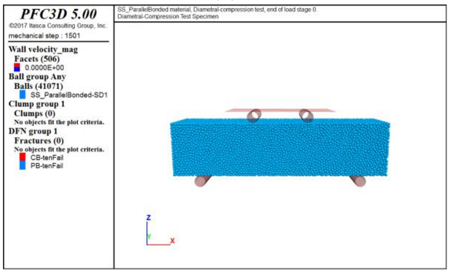



(c) (d)

Fig. 15 Experimental and numerical typical fracture surface development in specimens with 75% of recycled aggregate content (RAC75)




(a)




(b)

Fig. 16 Numerical model of a pervious concrete specimen for three-point bending test (a) and four-point bending test (b)

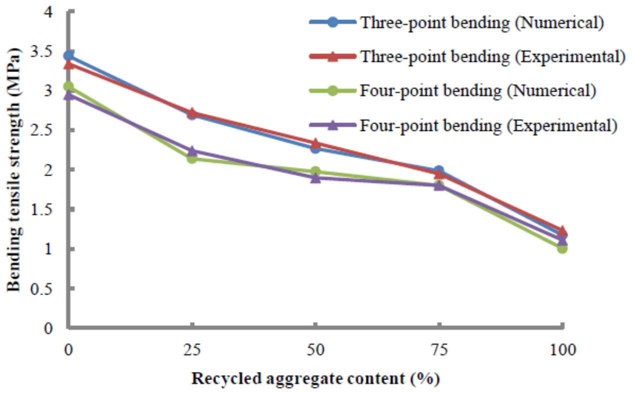
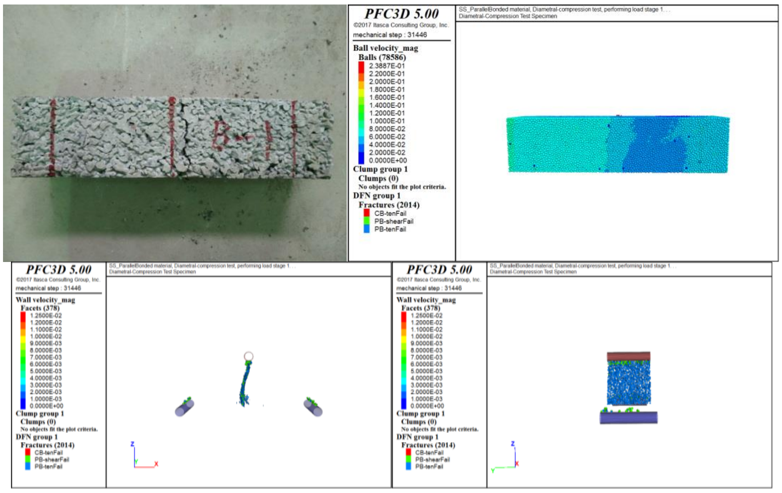


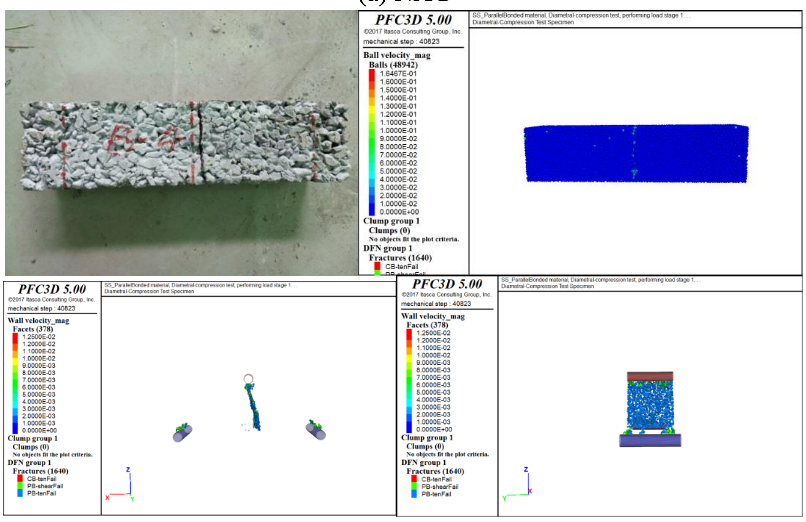

Fig. 17 Numerical and experimental splitting tensile strength depending on the recycled aggregate content

with the increase of loading force (see Fig. 14(c)), and the same is reproduced in the numerical model (as shown in Fig. 14(d)).

Fig. 15(a) shows the development of top crack of pervious concrete with 75% of recycled aggregate content.




(a) NAC




(b) RAC75

Fig. 18 Experimental and numerical typical fracture surface development in specimens with different recycled aggregate content for the three-point bending test

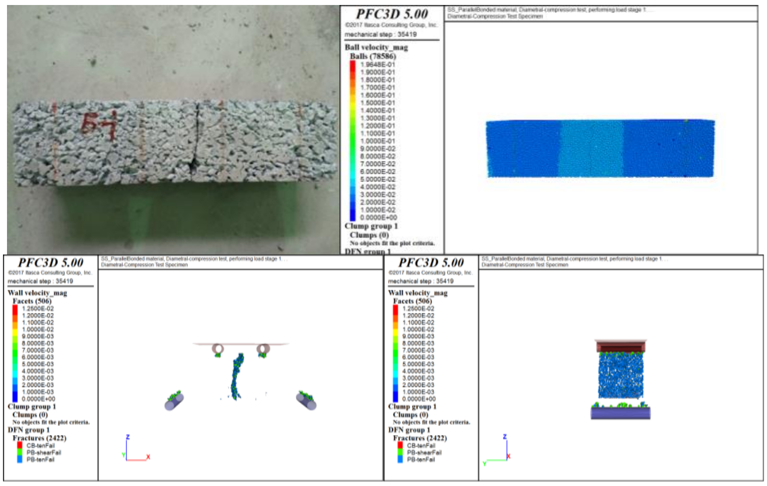
Compared with the top crack of concrete with 0% of recycled aggregate content, the fracture surface of the concrete is more smooth, which means that the bridging is weaker in the stress transfer between the left and right sides of the crack. By comparison, Fig. 15(b) shows that the mesoscopic fracture development model by the numerical simulation and the experimental results have similar fracture development trends. From Fig. 15(c) and Fig. 15(d), it can be seen that the concrete mixed with recycled aggregates has more and denser cracks than that of natural aggregate concrete. Because the bonding effect between recycled aggregate and cement slurry is weaker, and it is easy to cause interface damage and produce a large number of cracks.

### *4.4 Bending tensile behavior*

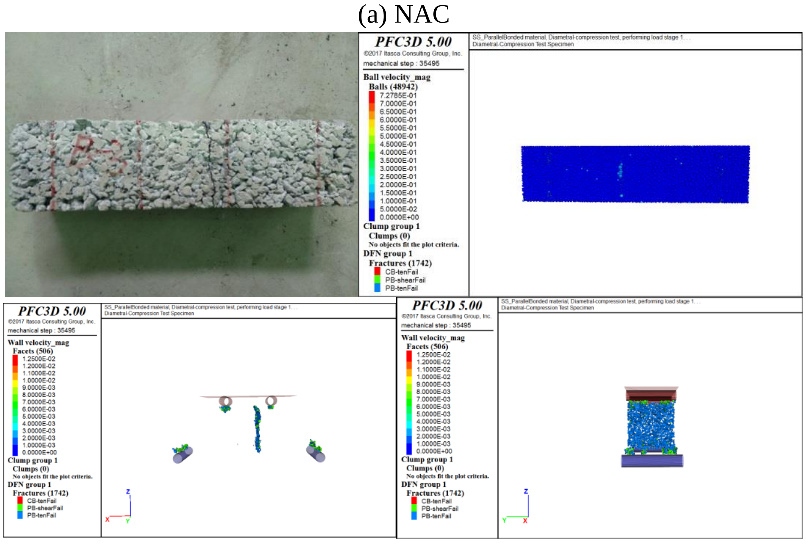
In order to make the numerical model in accordance with the test specimen, the model size is set to 100×100×400 mm. The simulation is still applied in the way of displacement loading, and the velocity of the top plate displacement is $1.67\times10^{-6}$ m/s (0.1 mm/min). Fig. 16(a) and Fig. 16(b) present the PFC$^{3D}$ models of pervious concrete specimen assembled for three-point bending and four-point bending test, respectively.

The relationship between the recycled aggregate content and the bending tensile strength of the concrete is obtained by numerical simulation, as shown in Fig. 17. The bending tensile strength of the numerical model decreases with the increase of recycled aggregate content. The three-point bending strength of the model ranges from 1.17 to 3.43 MPa. However the four-point bending strength of the model ranges from 1.00 to 3.05 MPa. The numerical simulation results are in good agreement with the laboratory experiments. This agreement shows that the meso-crack obtained by the numerical bending model reproduces the damage of the pervious concrete under the influence of the recycled aggregate content.

Fig. 18 shows a more intuitionistic comparison between the damage morphology of specimen in the three-point bending experiment and the internal fracture development in the corresponding numerical simulation. By the numerical simulation of the internal fractures development, it can be concluded that there are three places where the



(a) NAC



(b) RAC75

Fig. 19 Experimental and numerical typical fracture surface development in specimens with different recycled aggregate content for the four-point bending test

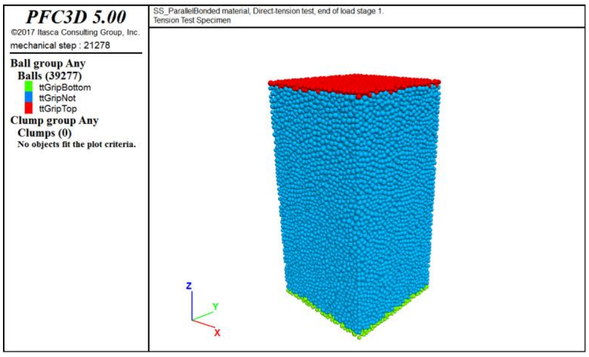



Fig. 20 Numerical model of a pervious concrete specimen for direct tension

stresses are larger when the beam is damaged, and they are the loading point and near the abutment, respectively. Most of the cracks in the middle of the beam are caused by tensile failure. Considering that tensile strength of concrete is very weak, so cracks first appear at the bottom of the beam.

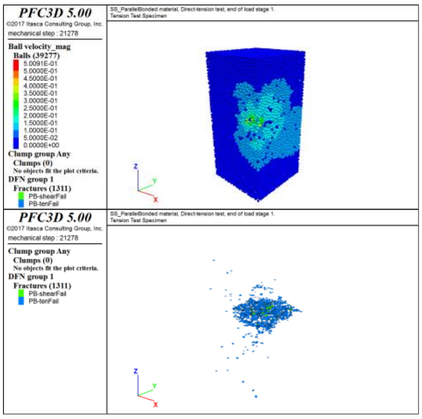
In addition, the stress distribution around the pores is uneven because of the existence of pores in the pervious concrete. And when stress is applied, it is easy to cause stress concentration and produce micro cracks. By laboratory experiments and numerical simulation, it can be seen that the fracture surface of RAC75 is smoother than that of NAC, which means the bridging effect is weakened in the stress transfer between the left and right ends of cracks (see Fig. 18(a) and Fig. 18(b)). Moreover, due to the low strength of recycled aggregate itself and the weak bonding effect with cement paste, the pervious concrete with high recycled aggregate content fractures prematurely in the center of the bottom, resulting in a decrease of the bending resistance.

Fig. 19 presents a visual comparison between failure modes of the experimental specimens in the four-point bending test and the corresponding numerical models with the internal fracture development. The failure modes of the specimens in the laboratory are consistent with those of the numerical simulation. Both of them are damaged by the tension in the central area of the bottom, cracked to form the oblique cracks of a certain angle, and the diagonal cracks angle of RAC75 are smaller than that of NAC (see Fig. 19), which is similar to the three-point bending test.

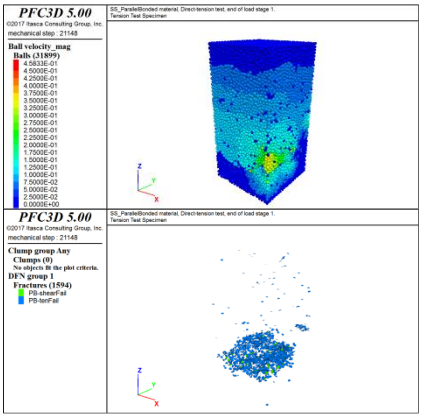
### *4.5 Direct tensile behavior*

In this numerical calculation, the influence of recycled aggregate content on the tensile strength of concrete is mainly considered. In keeping with the experimental conditions, the size of uniaxial tensile model is set to 100 mm×100 mm×200 mm. And the direct tension is controlled by the displacement, and the tensile velocity is 2 $\mu\varepsilon$/s. The direct tensile numerical model by PFC$^{3D}$ is shown in Fig. 20.

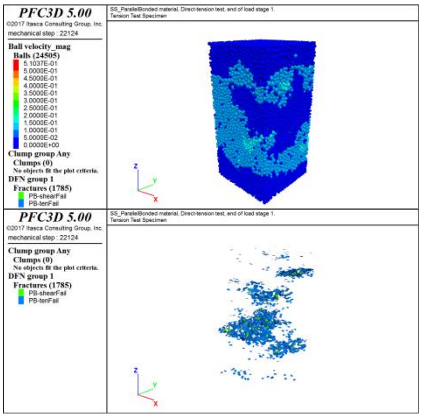
In order to analyze the influence of recycled aggregate content on the tensile strength of pervious concrete, pervious concretes with five kinds of recycled aggregate content are calculated and analyzed. The development of internal cracks of all kinds of concretes is shown in Fig. 21.



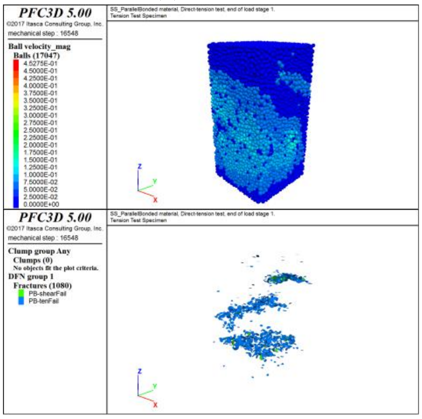

(a) NAC




(b) RAC25

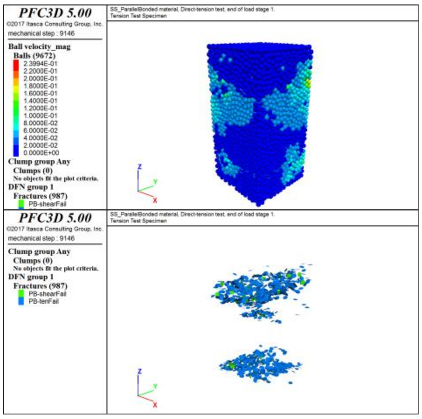



(c) RAC50




(d) RAC75

Fig. 21 Cracks development of pervious concrete with different recycled aggregate content under tensile breaking




(e) RAC100

Fig. 21 Continued

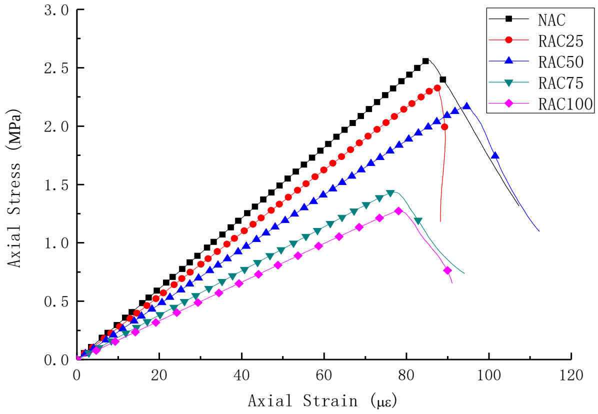



Fig. 22 Numerical data for uniaxial tensile stress-strain response

It can be seen that the cracks and the number of fracture layers increase obviously with the increase of the recycled aggregate content by the fracture development. Because the strength of RA is lower than that of NA, and the bonding effect with the slurry is weaker, which results in premature damage of pervious concrete mixed with recycled aggregate. And it will form a continuous fracture surface when continuously loaded, resulting in final damage of concrete specimen.

The stress-strain curve obtained by numerical simulation for direct tension is shown in Fig. 22. According to the stress-strain curve, the strength and elastic modulus of pervious concrete all decrease with the increase of recycled aggregate content, resulting in the failure of pervious concrete not to bear too great tensile force. The numerical simulation is consistent with the experimental results.

## 5. Conclusions

In this paper, the effects of the recycled aggregate content on the mechanical properties of the pervious concrete are studied by combining the laboratory experiment with the numerical simulation. The following conclusions can be drawn:

• The water absorption rate of recycled aggregate is larger than that of ordinary aggregate, which will reduce the water-cement ratio of concrete and resulting in incomplete hydration of cement. And the strength of the recycled aggregate itself is low and the porosity is high. These decisive factors result in an obvious weakening effect on the compressive strength of pervious concrete

• The lower strength of the recycled aggregates themselves cause the splitting failure plane to pass through the recycled aggregate instead of the interface transition zone (ITZ), which is more likely to result in the splitting failure.

• The recycled aggregate content has negative correlation to the three-point bending and four-point bending strength of pervious concrete. Because the strength of recycled aggregate itself is lower than that of natural aggregate, and the bonding effect between cement paste and recycled aggregate is weaker. So the pervious concrete with higher recycled aggregate content occur early fracture failure at the bottom center, resulting in the decrease of bending strength.

• The tensile strength and elastic modulus of pervious concrete decrease with different degrees with the increase of recycled aggregate content, which makes its bearing capacity of tension and fracture small. The more cracks generated in the pervious concrete and the weaker adhesion with the cement paste lead to premature rupture of the pervious concrete with recycled aggregates.

• In this paper, the numerical model is used to explain why the mechanical properties of concrete with recycled aggregates are reduced from the view point of microscopic mechanism. The numerical simulation by PFC$^{3D}$ shows that the fracture surface of the pervious concrete with recycled aggregates is smoother than that of the concrete with natural aggregates, which means that the bridging effect is weakened in the stress transfer at the left and right ends of the fracture. From the analysis of internal cracks development, the concrete with recycled aggregates more cracks than the concrete with natural aggregates, which results in premature fracture of recycled aggregate concrete.

## Acknowledgments

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## References

Abdollahzadeh, G., Jahani, E. and Kashir, Z. (2012), “Predicting of compressive strength of recycled aggregate concrete by genetic programming”, *Comput. Concrete*, **18**(2), 155-163.

Carneiro, C.A., Lima, P.R.L., Leite, M.B. and Filho, R.D.T. (2014), “Compressive stress-strain behavior of steel fiber reinforced-recycled aggregate concrete”, *Cement Concrete*

*Compos.*, **46**(4), 886-893.
Chen, X. and Bu, J. (2016), "Experimental study and modeling on direct tensile behavior of concrete under various loading regimes", *ACI Mater. J.*, **113**(4), 513-522.
Chen, X., Bu, J. and Xu, L. (2017), "Experimental study on cyclic tensile behavior of concrete under high stress level", *ACI Mater. J.*, **114**(5), 775-781.
Chen, X., Wu, S. and Zhou, J. (2014), "Variability of compressive strength of concrete cores", *J. Perform. Constr. Facil.*, **28**(4), 06014001
Choi, W.C. and Yun, W.C. (2012), "Compressive behavior of reinforced concrete columns with recycled aggregate under uniaxial loading", *Eng. Struct.*, **41**(3), 285-293.
Coelho, A. and Brito, J.D. (2011), "Economic analysis of conventional versus selective demolition-A case study", *Resour. Conserv. Recy.*, **55**(3), 382-392.
Ghorbel, E. and Wardeh, G. (2017), "Influence of recycled coarse aggregates incorporation on the fracture properties of concrete", *Constr. Build. Mater.*, **154**, 51-60.
Gomez-Soberón, J.M.V. (2002), "Porosity of recycled concrete with substitution of recycled concrete aggregate: an experimental study", *Cement Concrete Res.*, **32**(8), 1301-1311.
González, B. (2002), "Hormigones con áridos reciclados procedentes de demoliciones: dosificaciones, propiedades mecánicas y comportamiento estructural a cortante (Doctoral thesis)", Universidad de La Coruña.
Kou, S.C. and Poon, C.S. (2010), "Properties of concrete prepared with PVA-impregnated recycled concrete aggregates", *Cement Concrete Compos.*, **32**(8) 649-654.
Liang, J.F., Yang, Z.P., Yi, P.H. and Wang, J.B. (2017), "Stress-strain relationship for recycled aggregate concrete after exposure to elevated temperatures", *Comput. Concrete*, **19**(6), 609-615.
Malešev, M., Radonjanin, V. and Marinkovic´, S. (2010), "Recycled concrete as aggregate for structural concrete production", *Sustainab.*, **2**(5), 1204-1225.
Pieralisi, R. (2016), "Characterization and modelling of pervious concrete (Doctoral thesis)", Universitat Politècnica de Catalunya.
Rahal, K. (2007), "Mechanical properties of concrete with recycled coarse aggregate", *Build. Environ.*, **42**(1), 407-415.
Rao, A., Jha, K.N. and Misra, S. (2007), "Use of aggregates from recycled construction and demolition waste in concrete", *Resour. Conserv. Recy.*, **50**(1), 71-78.
Razaqpur, A.G., Fathifazl, G., Isgor, B., Abbas, A., Fournier, B. and Foo, S. (2010), "Produce High Quality Concrete mixes with recycled concrete aggregate", *Construction Waste Recycling and Civil Engineering Sustainable Development*, 11-35.
Sagoe-Crentsil, K.K., Brown, T. and Taylor, A.H. (2001). "Performance of concrete made with commercially produced coarse recycled concrete aggregate", *Cement Concrete Res.*, **31**(5), 707-712.
Sata, V., Ngohpok, C. and Chindaprasirt, P. (2016), "Properties of pervious concrete containing high-calcium fly ash", *Comput. Concrete*, **17**(3), 337-351.
Silva, R.V., Neves, R., Brito, J.D. and Dhir, R.K. (2015). "Carbonation behaviour of recycled aggregate concrete", *Cement Concrete Compos.*, **62**, 22-32.
Tabsh, S.W. and Abdelfatah, A.S. (2009), "Influence of recycled concrete aggregates on strength properties of concrete", *Constr. Build. Mater.*, **23**, 1163-1167.
Tavakoli, M. and Soroushian, P. (1996), "Strengths of recycled aggregate concrete made using field-demolished concrete as aggregate", *ACI Mater. J.*, **93**(2), 1-9.
Wagih, A.M., El-Karmoty, H.Z., Ebid, M. and Okba, S.H. (2013), "Recycled construction and demolition concrete waste as aggregate for structural concrete", *HBRC J.*, **9**(3), 193-200.
Xiao, J., Li, J., Sun, J. and Hao, X. (2004), ''Study on compressive strength of recycled aggregate concrete", *J. Tongji Univ.*, **32**(12), 1558-1561.
Younis, K. and Pilakoutas, K. (2013), "Strength prediction model and methods for improving recycled aggregate concrete", *Constr. Build. Mater.*, **49**(12), 688-701.

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