Mechanical properties and freeze-thaw durability of recycled aggregate pervious concrete

H B Liu¹, W J Li¹, H Yu¹, G B Luo¹ and H B Wei¹,²

¹College of Transportation, Jilin University, Changchun 130025, China

E-mail: weihb@jlu.edu.cn

Abstract. Recycled aggregate (RA) was obtained from waste cement concrete brick with the method of crushing and sieving. In order to research the effect of RA content on the properties of pervious concrete, RA was added to replace natural aggregate with equivalent quality method at different levels (25%, 50%, 75% and 100%). The natural aggregate pervious concrete and RA pervious concrete were prepared in the lab. The porosity, permeability, compressive strength, flexural strength and freeze-thaw (F-T) durability of RA pervious concrete were tested. The results indicated that the compressive strength and flexural strength of RA pervious concrete decreased with the increase of RA content. The rapid decreases for compressive strength and flexural strength occurred when the RA content was 25%-75% and 0%-25%, respectively. The porosity and permeability decreased slowly with the increasing RA content. F-T durability of RA pervious concrete was poorer than the natural aggregate pervious concrete. The incorporation levels had negative effect on the F-T durability, but the compressive strength loss of all groups after 25 F-T cycles met the requirement of the national standard. Although the mechanical properties and F-T durability of RA pervious concrete are not satisfied, it can still be used for sidewalks, parks and other light traffic roads.

1. Introduction

In recent years, with the quick economic development and the rise of city construction, the massive amount of the construction waste, if not treated in time, will cause serious environmental pollution [1]. Pervious concrete is considered as an environmentally friendly concrete due to its porous structure and high permeability. It has many environmental benefits, such as absorbing automobile exhaust, restoring groundwater supply, improving water quality and reducing water and soil pollution [2,3]. Moreover, due to its substantial pores, pervious concrete can not only improve the visibility and slip resistance of the road surface, but also abate the traffic noise and mitigate the urban heat island [4].

The recycle and reuse of non-degradable construction concrete waste has great social and economic potential [5,6]. RA is used in pervious concrete can effectively solve the environmental pollution caused by concrete waste. And it is an economic and environmental solution for the sustainable development [7]. In general, RA obtained from construction concrete waste is used to partially or completely replace the natural aggregate in the pervious concrete, which can achieve the purpose of cyclic utilization [8].

Zaetang et al [9] researched the mechanical properties of pervious concrete. The natural aggregate (NA) was replaced by the recycled concrete block aggregate (RBA) and recycled concrete aggregate (RCA) respectively with equivalent quality method at different incorporation levels (20%, 40%, 60%, 80% and 100%). The results showed that the compressive strengths of RBA and RCA pervious concrete increased first and then decreased with the increase of RA content. Both RBA and RCA
improved the compressive strength of pervious concrete. However, the RA content had little impact on the flexural strength of previous concrete. The experiment conducted by Güneyisi et al [10] indicated that the compressive strength of RA pervious concrete decreased with the increase of RA content. Zhu et al [11] obtained the same conclusions that the compressive strength and flexural strength of RA pervious concrete decreased with the increasing RA content.

The increase of RA content led to the loose structure and low density of pervious concrete, which resulted in the increasing porosity [12]. The permeability of RA pervious concrete, reported by Yap et al [13], increased with the increasing RA content due to the large porous network in RA mixture. Zhu [14] concluded that the RA content had little impact on the effective porosity and permeability of pervious concrete.

The F-T durability of pervious concrete is very important due to the porous structure [15]. Generally, the relative dynamic modulus of natural aggregate previous concrete without admixtures decreased to 60% of the initial value after 50 F-T cycles. Wang [16] conducted a comparative research on the F-T resistance of RA previous concrete (RPC), natural limestone aggregate previous concrete and ordinary concrete. The aggregate particle size, water-cement ratio and porosity were 5-20mm, 0.25 and 15%, respectively. The result indicated that the compressive strength loss and the mass loss of RPC were 5.6% and 2.3% respectively after 25 F-T cycles.

In addition, Sriravindrarajah et al [17], Berry et al [18], Chen et al [19] also conducted experimental research on the property of RA pervious concrete. Although many researchers have studied the basic mechanical properties and permeability of pervious concrete under different RA content, the research methods adopted were different and the conclusions obtained were not consistent. At the same time, there was little research on the relationship between the RA content and the F-T durability of pervious concrete. Therefore, in this paper, the RA obtained from waste concrete brick was used to research the influence of RA content on the mechanical properties and F-T durability of pervious concrete.

2. Materials

2.1. Materials
Portland cement with strength grade of P.O 42.5 was selected in this study. Single gradation of coarse aggregate was adopted to meet the requirement of permeability for pervious concrete. Two different aggregates, natural aggregate and recycled concrete aggregate showed in figure 1, were used as coarse aggregate. The natural granite coarse aggregate was obtained from a concrete mixing station in Jilin Province, China. The RA, produced by waste concrete brick, was obtained from Jilin Xusheng Environmental Protection Building Material Co., Ltd. (Jilin, China). The particle size of the two aggregates was 4.75-9.5 mm and the basic properties were shown in table 1. The water reducer was applied to improve the workability of pervious concrete.

![Figure 1](image1.png)

**Figure 1.** The natural aggregate (NA) and recycled aggregate (RA). (a) Natural aggregate and (b) Recycled aggregate.
Table 1. Basic properties of coarse aggregate.

| Physical index          | Natural aggregate (NA) | Recycled aggregate (RA) |
|-------------------------|------------------------|-------------------------|
| Particle size (mm)      | 4.75-9.5               | 4.75-9.5                |
| Apparent density (kg/m³)| 2786                   | 2673                    |
| Bulk density (kg/m³)    | 1534                   | 1450                    |
| Bulk porosity (%)       | 44.9                   | 45.8                    |
| Crushed value (%)       | 9.7                    | 11.1                    |
| Needle-like particle content (%) | 7.1            | 1.6                     |
| Water absorption rate (%) | 1.63               | 5.08                    |

2.2. Mixture proportion
The volumetric method was used for mixture design according to the Chinese national standard CJJ/T 135-2009. According to the previous researches conducted by our group [20,21], the water-binder ratio and porosity were selected as 0.30 and 15%. The amount of water reducer was 0.5% of the mass of cement. The RA was added with equivalent quality method and the incorporation levels were 25%, 50%, 75%, and 100%. The mixture proportion is shown in table 2.

Table 2. Mixture proportion (in kg/m³).

| Mix ID | RA content | Coarse aggregate | Cement | Water | Superplasticizer |
|--------|------------|------------------|--------|-------|------------------|
|        |            | NA               | RA     |       |                  |
| NA     | 0%         | 1503             | 0      | 483   | 145              | 2.41 |
| RA25   | 25%        | 1127             | 376    | 483   | 145              | 2.41 |
| RA50   | 50%        | 752              | 752    | 483   | 145              | 2.41 |
| RA75   | 75%        | 376              | 1127   | 483   | 145              | 2.41 |
| RA100  | 100%       | 0                | 1503   | 483   | 145              | 2.41 |

2.3. Specimen preparation
The cement paste encapsulating aggregate method and rodding method were used to prepare specimens. The 100 × 100 × 100 mm cubic specimen and 100 × 100 × 400 mm prismatic specimen were casted in the lab. The cubic specimen was used for porosity, permeability, compressive strength and F-T test and the prismatic specimen was used for flexural strength test. A total of 75 cubic specimens and 15 prismatic specimens were prepared. All specimens were demoulded after 24h and placed in standard-cured room with a temperature of 20 ± 2°C and a relative humidity of 95%.

2.4. Methods
2.4.1. Porosity. The pore structure of pervious concrete can be divided into three types: connected pore, semi-connected pore and closed pore. The connected pore and semi-connected pore are called effective pore. The effective porosity of the specimen can be calculated by following formula:

\[
P = \left[1 - \frac{m_2 - m_1}{\rho V_o}\right] \times 100\%
\]

where P is effective porosity (%); m₁ is the quality of the specimen submerged in water (g); m₂ is the saturated surface-dry quality of the specimen (g); \(\rho\) is the water density (g/cm³), and \(V_o\) is the volume of the specimen (cm³).

2.4.2. Permeability. The constant head permeability method was adopted in this paper. The basic
principle is that the discharged amount of water is directly related to the time when the water head height is constant. The permeability coefficient of pervious concrete is calculated by using equation (2).

\[ k = \frac{QL}{AHt} \]  

where \( k \) is the permeability coefficient of specimen (mm/s); \( Q \) is the discharged amount of water in \( t \) time (mm\(^3\)); \( L \) is the height of the specimen (mm); \( A \) is the upper surface area of the specimen (mm\(^2\)); \( H \) is the height of water head (mm), \( H = 150 \) mm; \( t \) is the time (s), \( t = 300 \) s.

2.4.3. Compressive strength and flexural strength. The compressive strength and flexural strength of pervious concrete are tested according to the Chinese national standard GB/T50081-2002. The flexural strength is tested by three-point bending test and the distance between two supporting points is 300 mm.

2.4.4. F-T durability. Rapid F-T method is used to evaluate the F-T durability of pervious concrete according to the Chinese national standard GB/T50082-2009. The crack and damage of the specimen were observed, and the compressive strength of the specimen was tested every 25 F-T cycles.

3. Results and analysis

3.1. Porosity and permeability

The experiment results with standard deviations of effective porosity and permeability coefficient are shown in table 3. The effect of RA content on the effective porosity and permeability coefficient is shown in figure 2. The relationship between effective porosity and permeability coefficient of pervious concrete is shown in figure 3.

| Mix ID | Effective porosity (%) | Permeability coefficient (mm/s) |
|--------|------------------------|---------------------------------|
|        | Mean                   | Standard Deviation              | Mean | Standard Deviation |
| NA     | 14.4                   | 0.13                            | 3.91 | 0.08               |
| RA25   | 14.2                   | 0.16                            | 3.88 | 0.09               |
| RA50   | 13.7                   | 0.27                            | 3.73 | 0.1                |
| RA75   | 13.4                   | 0.19                            | 3.61 | 0.07               |
| RA100  | 13.1                   | 0.19                            | 3.56 | 0.11               |

![Figure 2. Effective porosity and permeability coefficient versus RA content.](image1)

![Figure 3. The relationship between permeability coefficient and effective porosity.](image2)
The effective porosity has great impact on the permeability of pervious concrete. Figure 2 indicated that the effective porosity and permeability of pervious concrete decreased with the increasing RA content. When the RA content increased from 0% to 100%, the effective porosity decreased from 14.4% to 13.1% and the permeability coefficient decreased from 3.91 mm/s to 3.56 mm/s. The reason was that the density of RA was less than natural aggregate. The coarse aggregate in pervious concrete was added with equivalent quality method, which resulted in the increase of coarse aggregate volume and the decrease of the pore number. Thus, the porosity and permeability of pervious concrete were decreased. Figure 3 indicate that the permeability coefficient of pervious concrete increased with the increasing effective porosity. The permeability coefficient was positively correlated with effective porosity, which also explained the reason why permeability coefficient showed a downward trend with the increasing RA content in figure 2.

3.2. Compressive strength and flexural strength

Table 4 shows the compressive strength and flexural strength of pervious concrete. The influence of RA content on the compressive strength of pervious concrete is shown in figure 4. The influence of RA content on the flexural strength of pervious concrete is shown in figure 5.

| Mix ID | Compressive strength (MPa) | Flexural strength (MPa) |
|--------|---------------------------|------------------------|
|        | Mean | Standard Deviation | Mean | Standard Deviation |
| NA     | 22.2 | 0.42               | 4.84 | 0.11             |
| RA25   | 21.7 | 0.37               | 4.20 | 0.05             |
| RA50   | 19.7 | 0.59               | 3.97 | 0.09             |
| RA75   | 16.7 | 0.31               | 3.75 | 0.07             |
| RA100  | 15.9 | 0.35               | 3.73 | 0.08             |

Figure 4 showed that, with the increasing RA content, the compressive strength of pervious concrete presented a downward trend. The compressive strength of pervious concrete decreased from 22.2 MPa to 15.9 MPa with the loss of 28.3%. In addition, the decrease of compressive strength was strongly affected by the incorporation level of RA content. When the RA content was less than 25%, the compressive strength decreased slowly, when the RA content was more than 25%, the compressive strength decreased rapidly. The reasons for the decrease of compressive strength were as follows: (a) the RA was obtained by crushing the waste cement concrete brick, the internal damage of RA was produced during the crushing process, which resulted in the lower strength of RA than natural
aggregate; (b) due to the existence of hardened cement paste on the surface of RA, the adhesive property between RA and cement paste was weaker than that of natural aggregate; (c) the water imbibition of RA was larger than that of natural aggregate, part of the water in the mixture was absorbed by the RA, which resulted in incomplete hydration of cement. All the above decreased the compressive strength of RA pervious concrete.

Figure 5 indicated that the flexural strength of pervious concrete decreased with the increasing RA content, which was consistent with the effect of RA content on the compressive strength. The flexural strength decreased from 4.84 MPa to 3.73 MPa with the loss of 22.9%. The decrease degree of flexural strength was a little different from that of compressive strength. Compared with the decrease trend of compressive strength, when the RA content was less than 50%, the flexural strength decreased rapidly, when the RA content was more than 50%, the flexural strength decreased slowly. The decrease of flexural strength of RA pervious concrete also attributed to the low strength of RA, weak adhesive property and large water absorption of RA.

3.3. F-T durability
The compressive strength and its loss of pervious concrete after 25, 50, 75 and 100 F-T cycles are shown in table 5. The effect of F-T cycles on the compressive strength of RA pervious concrete is shown in figure 6. The compressive strength loss of RA pervious concrete under F-T cycles are shown in figure 7.

| Mix ID | Compressive strength (MPa) | Compressive strength loss (%) | Compressive strength (MPa) | Compressive strength loss (%) | Compressive strength (MPa) | Compressive strength loss (%) | Compressive strength (MPa) | Compressive strength loss (%) |
|--------|---------------------------|-------------------------------|---------------------------|-------------------------------|---------------------------|-------------------------------|---------------------------|-------------------------------|
| NA     | 21.2                      | 4.5                           | 18.1                      | 18.5                          | 16.7                      | 24.8                          | 14.2                      | 36.0                          |
| RA25   | 20.5                      | 5.5                           | 17.3                      | 20.3                          | 15.9                      | 26.7                          | 12.9                      | 40.6                          |
| RA50   | 18.4                      | 6.6                           | 14.2                      | 22.8                          | 12.5                      | 36.5                          | 11.2                      | 43.1                          |
| RA75   | 14.7                      | 12.0                          | 11.9                      | 28.7                          | 10.4                      | 37.7                          | 8.4                       | 49.7                          |
| RA100  | 13.5                      | 15.1                          | 10.9                      | 31.4                          | 9.6                       | 39.6                          | 7.1                       | 55.3                          |

Figure 6. Compressive strength versus F-T cycles.

According to the figure 6, the conclusion can be drawn that, for all pervious concrete mixtures, when the incorporation levels of RA content were the same, the compressive strength of pervious concrete decreased with the increase of F-T cycles, which showed that the F-T resistance of pervious concrete gradually deteriorated under F-T cycles. When the number of F-T cycles was the same, the
compressive strength of RA pervious concrete decreased with the increase of RA content. Compared with the compressive strength of 14.2 MPa for natural aggregate pervious concrete under 100 F-T cycles, the compressive strengths of 75% and 100% RA pervious concrete were only 8.4 MPa and 7.1 MPa. The F-T resistance was greatly reduced.

Figure 7 showed that the compressive strength loss of pervious concrete gradually increased with the increasing F-T cycles, and the compressive strength loss increased with the increasing RA content when the F-T cycles were the same. Compared with the natural aggregate pervious concrete, the RA pervious concrete had higher compressive strength loss. And the higher RA content, the higher compressive strength loss. For all pervious concrete mixtures, when the F-T cycles were 25, the compressive strength loss was 4.5% to 15.1%, which met the requirement of 20% for pervious concrete in the Chinese national standard CJJ/T 135-2009 and indicated the application of RA pervious concrete in F-T regions was feasible.

4. Conclusions
In this study, the RA pervious concrete was prepared and investigated. According to the experiment results, several conclusions can be concluded.

- Due to the adoption of equivalent quality replacement method, the effective porosity and permeability of pervious concrete gradually decreased with the increasing RA content.
- The addition of RA decreased the compressive strength and flexural strength of pervious concrete, but the pervious concrete contained different content of RA presented acceptable compressive strength and flexural strength.
- The F-T durability of RA pervious concrete was not equal to that of natural aggregate pervious concrete and the F-T durability of pervious concrete decreased with the increase of RA content.
- Although the addition of RA was negative to the performance of pervious concrete, it was still practicable to use it in sidewalks, parks and light traffic roads.

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References
[1] Bravo M, de Brito J, Pontes J and Evangelista L 2015 Mechanical performance of concrete made with aggregates from construction and demolition waste recycling plants J Clean Prod. 99 59-74
[2] Yahia A and Kabagire K D 2014 New approach to proportion pervious concrete Constr Build Mater. 62 38-46
[3] Zhang S H and Guo Y P 2015 Analytical equation for estimating the stormwater capture efficiency of permeable pavement systems J Irrig Drain Eng. 141 06014004
[4] McCain G N and Dewoolkar M M 2010 Porous concrete pavements: mechanical and hydraulic properties Transport Res Rec. 2164 66-75
[5] Ibrahim H A and Razak H A 2016 Effect of palm oil clinker incorporation on properties of pervious concrete Constr Build Mater. 115 70-7
[6] Tam V W Y, Butera A and Le K N 2016 Carbon-conditioned recycled aggregate in concrete production J Clean Prod. 133 672-80
[7] Su H, Yang J, Ling T C, Ghataora G S and Dirar S 2015 Properties of concrete prepared with waste tyre rubber particles of uniform and varying sizes J Clean Prod. 91 288-96
[8] 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. 31 707-12
[9] Zaetang Y, Sata V, Wongsa A and Chindaprasirt P 2016 Properties of pervious concrete
containing recycled concrete block aggregate and recycled concrete aggregate Constr Build Mater. 111 15-21

[10] Güneyisi E, Gesoğlu M, Kareem Q and Ipek S 2016 Effect of different substitution of natural aggregate by recycled aggregate on performance characteristics of pervious concrete Mater Struct. 49 521-36

[11] Zhu X Y, Chen X D, Shen N, Tian H X, Fan X Q and Lu J 2018 Mechanical properties of pervious concrete with recycled aggregate Comput Concrete 21 180-93

[12] Wang Y M, Deng Z H, Tan Y H and Yang H F 2015 Permeability and strength of porous concrete made with recycled aggregate Concrete 7 26-30

[13] Yap S P, Chen P Z C, Goh Y X and Ibrahim H A 2018 Characterization of pervious concrete with blended natural aggregate and recycled concrete aggregates J Clean Prod. 181 155-65

[14] Zhu J C 2014 Study on the content of recycled aggregate in recycled pervious concrete China Concrete and Cement Products 10 6-11

[15] Lund M S M, Kevern J T, Schaefer V R and Hansen K K 2017 Mix design for improved strength and freeze-thaw durability of pervious concrete fill in Pearl-Chain Bridges Mater Struct. 50 1-15

[16] Wang J Q 2016 Test research on the shrinkage and frost-resistance of recycled aggregate porous concrete Industrial Construction 46 103-6

[17] Sriravindrarajah R, Wang N D H and Ervin L J W 2012 Mix design for pervious recycled aggregate concrete Int J Concr Struct M. 6 239-46

[18] Berry B M, Suozzo J M, Anderson I A and Dewoolkar M M 2012 Properties of pervious concrete incorporating recycled concrete aggregate Transportation Research Board Annual Meeting (Washington, D.C)

[19] Chen S K 2018 Influence of recycled aggregate proportion performance of recycled pervious concrete performance Acta Mater Compos Sin. 35 1590-8

[20] Liu H B, Luo G B, Wei H B and Yu H 2018 Strength, permeability, and freeze-thaw durability of pervious concrete with different aggregate sizes, porosities, and water-binder ratios Appl Sci. 8 1217

[21] Liu H B, Luo G B, Gong Y F and Wei H B 2018 Mechanical properties, permeability, and freeze–thaw resistance of pervious concrete modified by waste crumb rubbers Appl Sci. 8 1843