Abrasion Resistance Improvement of Recycled Aggregate Pervious Concrete with Granulated Blast Furnace Slag and Copper Slag

Shouwei Jian1*, Bo Wei2, Xiao Zhi3, Hongbo Tan4, Baodong Li5, Xiangguo Li3 and Yang Lv3

Abstract
The poor abrasion resistance of recycled aggregate pervious concrete (RAPC) limits its application. Granulated blast furnace slag (GBFS) and copper slag (CS) were used as mineral admixtures to replace cement in RAPC for improving the abrasion resistance. At the 10% GBFS replacement level, 5% to 25% of CS was added in RAPC respectively, which reduced the consumption of the cement. The effects of GBFS and CS on paste fluidity, porosity, permeability, compressive strength and abrasion resistance were evaluated. RAPC exhibited an excellent abrasion resistance after adding GBFS and CS. In this case, 10% blended amount was the optimal amount of GBFS and CS. Compared with the single cement group, the abrasion resistance increased by 38.78%, which is mainly because the fayalite in CS supplies good abrasion resistance, whereas the GBFS also plays an important role. The mechanism was studied via X-ray diffraction analysis and microhardness. The porosity and permeability of the RAPC increased with the CS replacement level. Moreover, the leaching concentration of heavy metal ions in the prepared RAPC was significantly low, indicating that RAPC could be applied safely. The results not only provides a feasible technical means for the large-scale utilisation of CS but also presents a theoretical basis for the improvement of RAPC abrasion resistance.

1. Introduction

Several cities worldwide have been experiencing pressing challenges on the flood problems, especially with the extreme weather. Pervious concrete (PC) refers to a form of concrete with an interconnected pore structure that enables the penetration of rainwater below the surface of pervious materials; it could be used to effectively store underground water resources, reduce storm-water runoff and alleviate heat island effects. Owing to the incessant exploitation of natural aggregates (NAs), which has led to the continuous depletion of resources, the use of recycled aggregates (RAs) to prepare PC has become a topical research focus in recent years (Bhutta et al. 2013; Li et al. 2020b; Liu et al. 2019; Yap et al. 2018).

The permeability, porosity and compressive strength of recycled aggregate pervious concrete (RAPC) usually range between 1.4 and 12.2 mm/s, 15% and 35% and 5 and 24 MPa, respectively (Aliabdo et al. 2018; Zhang et al. 2017). Notably, RAPC is an environmentally friendly building material that is used in several scenarios, such as traffic-busy parks, runways, sidewalks and parking lots. However, the PC prepared from RAs has poor abrasion resistance. El-Hassan et al. (2019) found that in comparison with PC made from NAs, RAPC had a reduction in abrasion resistance of 18% to 22%. Researchers have also improved the abrasion resistance of concrete by changing different types of aggregates or adding granulated-blast furnace slag (GBFS) into cement paste. Gesoğlu et al. (2014) replaced NAs with waste tyre rubber and found that when the replacement rate was 20%, the abrasion mass rate decreased by 81%. Gaedicke et al. (2014) reported that after replacing 30% of cement with GBFS, the abrasion resistance of PC improved. Moreover, GBFS was proved to be beneficial toward improving the abrasion resistance of PC (Kumar 2017).

The abrasion resistance of RAPC is mainly affected by the physical properties of RAs and cement paste. Additionally, the tightness of the interfacial transition zone (ITZ) may contribute to the inferior abrasion resistance of RAPC. Poor abrasion resistance may lead to the clogging problems in the later stage, which significantly affects the service life of RAPC.

Copper slag (CS) is a by-product generated from copper smelting and conversion processes (Lye et al. 2015). For every tonne of copper produced, approximately 2.2 tonnes of CS is generated (Gorai et al. 2003). However, the high Fe2O3/SiO2 ratio in CS inhibits high pozzolanic activity, therefore, CS may have a "micro-aggregate effect" similar to fly ash, which could improve the abrasion resistance of the paste (Li et al.
2014; Pan et al. 1998), while the excessive addition of CS could also result in bleeding, which limits large-scale applications (Feng et al. 2020). Recently, studies have shown that adding CS to concrete could improve the mechanical properties of the latter. Al-Jabri et al. (2009) used CS instead of fine sand to prepare high-strength concrete and found that as the replacement rate of CS increased, the strength and durability of the concrete improved. The CS replacement rate could endow the concrete with the highest strength, abrasion resistance and durability. (Panda et al. 2020), prepared fine aggregate CS concrete and found that the improvement in the performance of the concrete was mainly because of the better particle accumulation and natural pozzolanic activity in the CS.

However, few studies have been conducted on applying CS to PC (Lori et al. 2019). The large amount of fayalite in CS results in good strength in micro-particles, which suggest that it could have an application potential in RAPC (Cai et al. 2019; Panda et al. 2020). What’s more, it is evident that the application of CS in PC is not only beneficial toward rationally utilising solid waste but also feasible for reducing resource consumption and the greenhouse gas emissions generated by the production of cement, which has great exploratory significance and application value (Jian et al. 2020; Kajaste and Hurme 2016; Shi et al. 2008; Tan et al. 2019a, 2019b; Zhang et al. 2020).

In order to improve the abrasion resistance of RAPC, the feasibility of application of GBFS and CS in RAPC were investigated. The influence of the CS content on the porosity, permeability, compressive strength and abrasion resistance of RAPC was studied. Furthermore, the mechanism was analysed via X-ray diffraction (XRD), microhardness and Energy Dispersive Spectrometer (SEM-EDS). Finally, a heavy metal ion leaching experiment testing program was performed to evaluate the safety of the RAPC.

2. Materials and Methods

2.1 Materials

In this experiment, the cementitious materials were Type I Portland cement, GBFS and CS. The physical properties and chemical compositions of the cementitious materials are listed in Table 1 and the particle size distribution is shown in Fig. 1. The CS, which was obtained from the Hubei Dajiang Environmental Technology Co., Ltd., contained a small amount of heavy metal compounds, as shown in Table 1. The XRD patterns are shown in Fig. 2; CS generally consists of SiO$_2$, Fe$_2$O$_3$ and a limited amount of other compounds, with an amorphous phase of complex silicates formed through rapid water cooling.

The RAs in RAPC were obtained by crushing coarse RAs (30 to 50 mm). The particle sizes of the RAs ranged from 5 to 10 mm and their surfaces were attached to cement mortar, therefore, its water absorption rate could reach 6.73%. Their physical properties are listed in Table 2. Furthermore, a polycarboxylate superplasticiser (SP) with a solid content of 100% was added to the RAPC to improve the paste fluidity by adjusting the appropriate water-to-cement ratio ($w/c$).

![Fig. 1 Particle size distribution of cementitious materials.](image1)

![Fig. 2 XRD pattern of CS.](image2)

Table 1 Chemical compositions and other physical properties of cementitious materials.

| Constituents (%) | Cement | GBFS | CS |
|------------------|--------|------|----|
| SiO$_2$          | 21.31  | 33.40| 33.33|
| CaO              | 58.15  | 39.25| 3.83 |
| Al$_2$O$_3$      | 5.72   | 15.15| 5.48 |
| Fe$_2$O$_3$      | 3.33   | 0.31 | 49.24|
| MgO              | 2.52   | 7.67 | 1.59 |
| Na$_2$O          | 0.35   | 0.38 | 1.02 |
| K$_2$O           | 0.90   | 0.39 | 0.80 |
| SO$_3$           | 3.98   | 2.38 | 0.84 |
| Cr$_2$O$_3$      | -      | -    | 0.138|
| MnO              | -      | -    | 0.182|
| CuO              | -      | -    | 0.315|
| ZnO              | -      | -    | 1.656|
| PbO              | -      | -    | 0.270|
| LOI              | 2.98   | 0.11 | 0.62 |
| Specific surface area (m$^2$/kg) | 450    | 976  | 125  |
2.2 Mix proportions of RAPC

As shown in Table 3, a total of eight sets of mixtures were designed, including a common RAPC with cement as the cementing material for the blank group and seven sets of RAPC with GBFS or CS mixed. The cementing material had a density of 370 kg/m³, aggregate-to-cement ratio of 3.5, according to the American Standard ASTM C29 and ASTM C1688, the design porosity of 24% measured via the volume method. The mixes were labelled as GBFSx and CSy, where x and y were the mass ratios of GBFS and CS, respectively, in the cementitious materials. For instance, GBFS5% means that GBFS accounts for 5% of the mass of cementitious materials, whereas cement accounts for 95%. Similarly, GBFS10% implies that GBFS constitutes 10% of the total mass of cementitious materials, whereas the mass ratio of cement is 90%. Furthermore, G10%-CSy (y=5%, 10%, 15%, 20% and 25%) indicated that the mass ratio of GBFS was 10%, those of CS were 5%, 10%, 15%, 20% and 25%, whereas those of cement were 85%, 80%, 75%, 70% and 65%. Because CS has a large particle size and low pozzolanic activity and too much mixing would increase paste fluidity, different w/c values are used in the formulation to ensure good RAPC performance. When the CS contents were 5% and 10%, the w/c of RAPC was 0.30 and the w/c of 15% to 25% was 0.27. The amount of SP added was 0.05% of the mass of the cementitious material.

Table 3 Mix proportions of RAPC (kg/m³).

| Mix Designation | Design porosity | RA  | Cement | GBFS | CS  | Water | SP   |
|----------------|----------------|-----|--------|------|-----|-------|------|
| C100%          | 24.0%          | 1295| 370.0  | -    | -   | 111   | 0.185|
| GBFS5%         | 24.0%          | 1295| 351.5  | 18.5 | -   | 111   | 0.185|
| GBFS10%        | 24.0%          | 1295| 333.0  | 37.0 | -   | 111   | 0.185|
| G10%-CS5%      | 24.4%          | 1295| 314.5  | 37.0 | 18.5| 111   | 0.185|
| G10%-CS10%     | 24.8%          | 1295| 296.0  | 37.0 | 37.0| 111   | 0.185|
| G10%-CS15%     | 25.2%          | 1295| 277.5  | 37.0 | 55.5| 99.9  | 0.185|
| G10%-CS20%     | 25.6%          | 1295| 259.0  | 37.0 | 74.0| 99.9  | 0.185|
| G10%-CS25%     | 26.0%          | 1295| 240.5  | 37.0 | 92.5| 99.9  | 0.185|

2.3 Mixing and preparation of specimens

The concrete was prepared in a power rotary mixer according to the American Standard ASTM C192. First, RA and 50% water were mixed for 1 minute to ensure that the aggregate was fully wetted and then the cementitious materials (cement, GBFS and CS) were added, while stirring continued for 1 minute to ensure that the aggregate evenly coated the paste. Finally, the remaining water and SP were added and stirred for 2 minutes, poured into two layers of a 100×100×100 mm³ mould, compacted and covered with a plastic cling film to prevent water evaporation. After curing at room temperature for 24 hours, the samples was demoulded and sent to a standard curing room for 28 days for testing.

2.4 Test method

2.4.1 Paste fluidity

The paste fluidity of PC is an important indicator; excessive fluidity could lead to pore blockage, while insufficient fluidity leads to inadequate connections between aggregates and affects its mechanical properties, thereby resulting in poor work performances. Paste fluidity tests were conducted using a mini-slump method according to the American standard ASTM C1437. Each group was tested three times and the average of the three measured values was used, as depicted in Fig. 3.

2.4.2 Connected porosity

The total porosity of PC includes both connected and non-connected voids, wherein the former is the main factor affecting permeability. Based on the American Standard ASTM C1754/C1754M-12, the sample size was first measured with a Vernier calliper. The gravity and buoyant weight of the sample in water were then determined. The connected porosity, $P$, could be calculated using Eq. (1):

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

where $P$ is the connected porosity of the sample (%), $m_2$ is the constant weight of the sample after drying at 65°C for 28 hours (kg), $m_1$ is the buoyant weight of the sample in water (kg), $\rho$ is the density of water (kg/m³) and $V$ is the volume of the sample (m³). Additionally, two samples of 100×100×100 mm³ in each group were sliced and the thickness was controlled.
at 15 to 20 mm. Therefore, each group of samples could produce 16 effective cross sections. According to the color scale difference between the aggregate, paste and holes in the slice, the porosity of the slice could be obtained after processing and calculation by Image Pro Plus software (version 6.0), as depicted in Fig. 4 (Ni et al. 2021; Yu et al. 2019).

2.4.3 Permeability
Based on the American Standard ASTM C1701, the constant head method was used to test the water permeability coefficient. During the test, plasticine was used to seal the four sides of the test block to ensure that water could only flow through the upper and lower surfaces. The permeability coefficient \( k_T \) was calculated according to Darcy’s law (Simmons 2008), as shown in Eq. (2):

\[
k_T = \frac{Q L}{A H \Delta t}
\]

where \( k_T \) is the coefficient of permeability (mm/s), \( Q \) is the water flow (mL), \( L \) is the thickness of the test block (mm), \( A \) is the cross-sectional area of the test block (mm²), \( H \) is the water head height (mm) and \( t \) is the test time (s).

2.4.4 Compressive strength
According to the American (ASTM C39) standard, the compressive strength of the 28-day concrete test block and paste was measured.

2.4.5 Abrasion resistance
The abrasion resistance of PC was tested according to the American (ASTM C1747) standard and the abrasion mass loss of the test block was measured using a Los Angeles abrasion machine, as shown in Fig. 5. According to the test procedure, three samples were tested in each group by placing them into the abrasion machine and tested for 500 revolutions. The percentage abrasion mass loss \( A \) was calculated using Eq. (3):

\[
A = \left( \frac{m_f - m_i}{m_i} \right) \times 100\%
\]

where \( A \) is the abrasion mass loss of the sample (%), \( m_f \) is the constant weight of the sample after drying (kg) and \( m_i \) is the mass of the sample after the test (kg).

2.4.6 Microstructure
XRD (D/Max-RB) was used to test the phase composition of the paste in the range of 5 to 70° at a scan rate of 2°/min. Preparation test blocks was with a 1:1 ratio of RA and cementitious material. After curing for 28 days under standard conditions, nanoindentation tests on the polished samples were performed using a NANOVER CB500 hardness tester. Figure 6(a) is the indentation of the indenter on the sample, with the indentation hardness \( H \) and indentation modulus \( M \) being derived by analyzing the \( P-h \) curve and scale model, as shown in Eqs. (4), (5) and (6) (Sorelli et al. 2008). As shown in Fig. 6(b), the 100×100 µm area in the paste is selected for testing and every 10 µm in the horizontal and vertical directions is a test point and the maximum load of the indenter is 10 mN for 10 seconds, then a constant unloading. The hardness and indentation modulus data could be read by the instrument (Xiao et al. 2013).
\[
H = \frac{P_{\text{max}}}{A_c} \quad (4)
\]

\[
S = \frac{dP}{dh} \quad (5)
\]

\[
M = \frac{\sqrt{\pi}}{2} \cdot \frac{S}{\sqrt{A_c}} \quad (6)
\]

where \(H\) is the indentation hardness (GPa), \(P_{\text{max}}\) is maximum load value (mN), \(A_c\) is the contact area between the indenter and the sample surface (\(\mu\)m\(^2\)), \(S\) is the unloading indentation stiffness (N/m), \(h\) is the load depth and \(M\) is the indentation modulus (GPa).

A Field Emission Scanning Electron Microscope (FE-SEM, QUANTA FEG 450, FEI Co, USA) equipped with an energy dispersion spectrometer was used for qualitative and semi-quantitative analysis of the elements of the samples. After that, they were put into the sample chamber and Energy Dispersive Spectroscopy (EDS) was conducted.

2.4.7 Environmental safety assessment

According to Table 1, CS contains heavy metal elements, such as Cr, Mn, Cu, Zn, Mo, Ba and Pb. As PC is often in a water flow environment and there may be acid rain in some areas, it must be ensured that RAPC is not detrimental to the environment. A leaching test was performed according to the toxicity characteristic leaching procedure (TCLP) (Gao et al. 2020; Li et al. 2021). The sample size of G10%-CS25% was crushed to less than 5 mm, whereas a glacial acetic acid solution with pH of 2.88 was used as the extraction solution. The concentrations of heavy metal ions in the leachate were measured via atomic absorption spectrometry (AS, CONTRAA-700, Germany), with a hollow cathode lamp current of 6.0 mA.

3. Results and discussion

3.1 Paste fluidity

According to the previous reports, the spread value of the PC paste is between 150 and 190 mm and has good working performance (Chindaprasirt et al. 2008; Yang et al. 2020). Owing to the larger particle size of CS and low water absorption, bleeding occurs when its proportion in the cementitious material is significantly high (Al-Jabri et al. 2011; Shi et al. 2008). Therefore, a paste fluidity test was performed to explore the appropriate \(w/c\) under different CS content conditions.

Figure 7(a) shows the spread value of the paste with GBFS. The spread values of the blank group, GBFS5% and GBFS10% were 180, 174 and 170 mm, respectively. The addition of GBFS could reduce the paste fluidity, which may be related to the large specific surface area of GBFS. Evidently, when the GBFS content is 10%, there is a greater potential for reducing the fluidity of the paste after adding CS. Fig. 7(b) shows the spread value of the paste with GBFS10% and CS. For the same \(w/c\), the paste fluidity increases with the CS content. At \(w/c=0.30\), the spread value of G10%-CS15% exceeded 190 mm, which is not conducive to the preparation of RAPC. Therefore, when the CS content is between 15% and 25%, the \(w/c\) is adjusted to 0.27 such that the spread value is also within an appropriate range of 160 to 190 mm.

3.2 Basic properties

3.2.1 Connected porosity

Figure 8 shows the porosity measured and analysed using Image Pro Plus 6.0. In Fig. 8(a), the porosity of the blank group was 22.8%, which is very close to the design porosity of 24%, it is caused by the small color difference between the aggregate and the hole. After adding 5% and 10% GBFS, the void ratio changed minimally. As shown in Fig. 8(b), when the CS content increased from 5% to 25%, the porosity increased from 23.1% to 25.1%, representing an increase of 8.7%. Moreover, G10%-CS25% increased by 10.1% compared to that of the blank group. Additionally, the porosity analysed by Image Pro Plus...
6.0 software has the same regularity as the actual measurement.

3.2.2 Permeability

Figure 9 shows the permeability coefficient of the RAPC. As shown in Fig. 9(a), the permeability coefficient of the blank group was 4.58 mm/s. Compared with the blank group, GBFS5% and GBFS10% exhibit an inconsiderable change in permeability, which are 4.33 and 4.39 mm/s respectively and are similar to the change in porosity. In Fig. 9(b), with an increase in the CS replacement rate, the permeability coefficient gradually increased, both show a good linear relationship. The permeability of G10%-CS5% and G10%-CS25% is 4.48 mm/s and 5.33 mm/s, respectively, representing an increase of 19.0%. After CS was used to replace cement, the volume of the paste became smaller and the increase in permeability was related to the increase in porosity, which may also correspond to the pore radius and tortuosity (Torskaya et al. 2014).

3.2.3 Compressive strength

The fracture modes of PC are generally divided into three types: aggregate fracture, aggregate and ITZ of paste fracture and paste fracture (Brake et al. 2016; Rehder et al. 2014). The compressive strength of the 28-day test block was tested and the specific reasons for the change in compressive strength were analysed.

The 28-day compressive strengths of the RAPC are shown in Fig. 10. The compressive strengths of RAPC in the blank group were 14.2 MPa, which decreased slightly after adding GBFS; this is consistent with previous research (Bilir et al. 2017). With an increase in the CS content, the compressive strength of RAPC gradually decreased. The compressive strengths of the RAPC in G10%-CS25% were 9.3 MPa, which decreased by 34.5% compared with the blank group. This is consistent with an earlier report that CS has an adverse effect on the early strength development of concrete; thus, the replacement ratio should not be significantly high (Al-Jabri et al. 2002, 2006). In Fig. 10, it could also be found that the r_w/c in G10%-CS15% to G10%-CS25% was adjusted to 0.27 and the compressive strength continued to decrease. This indicates that CS has an adverse effect on the strength development of the prepared RAPC, especially when the content exceeds 10%.

3.3 Abrasion resistance

Figure 11 shows the abrasion mass loss of RAPC at 28 days, the abrasion mass loss of GBFS5% decreased from 17.15% to 15.16% compared with the blank group,
which represented a decrease of 11.60%, indicating that GBFS could considerably improve the abrasion resistance of RAPC; when the GBFS was added at the 10% level, the abrasion rate dropped to 12.32%, which was 28.16% lower than that of the blank group, thereby further illustrating the contribution of GBFS toward improving abrasion resistance. The abrasion mass loss of G10%-CS10% is the lowest at 10.50%, which is 38.78% lower than that of the blank group, indicating that the optimal amount of CS is 10%. When rw/c is 0.27, the abrasion mass loss of G10%-CS15% to G10%-CS25% remains greater than that of G10%-CS10%, thereby indicating that a significant amount of CS has a greater impact on the compactness of the paste structure, which could improve the abrasion resistance of the RAPC.

It could be found that GBFS and CS can effectively improve the abrasion resistance of RAPC. It may be that GBFS and CS with different particle combinations improve the compactness of the paste. In addition, CS with high content of fayalite could act as a "micro-aggregate" and provide good abrasion resistance for RAPC. However, when the CS content exceeds 10%, the abrasion resistance gradually decreases. This may be due to the large particle size and low pozzolanic activity of CS, which leads to a decrease in the densification of the paste, but the abrasion resistance of the RAPC mixed with CS is higher than that of the blank group.

3.4 Microstructure
3.4.1 XRD analysis
Figure 12 shows the XRD patterns of the paste. In Figs. 12(a) and 12(b), the peak intensity of ettringite did not change significantly. The peak intensities of C3S/C2S and portlandite decreased with an increase in GBFS and CS substitution, which was caused by the decrease in cement hydration products. Additionally, a diffraction peak of calcite was observed, which could have been caused by the carbonisation of the paste (Jiang et al. 2020a, 2020b; Zhang et al. 2021). According to related studies, the abrasion resistance of concrete is negatively correlated with the content of portlandite, which explains why the abrasion resistance of RAPC increases after GBFS is added (He et al. 2019). Furthermore, with an increase in the CS content, the peak intensity of fayalite increased gradually, indicating that fayalite did not participate in the hydration reaction. The presence of fayalite further improved the abrasion resistance of RAPC.

3.4.2 Microhardness test
The results of nanoindentation are shown in Fig. 13. It can be observed from Fig. 13(a) that the hardness change trend of the sample was consistent with the abrasion resistance mentioned above. The hardness of the blank group was 1.46 GPa, increasing gradually after adding GBFS. When 10% GBFS and 10% CS were added, the hardness was the highest at 2.00 GPa, which is 37.0% higher than that of the blank group. According to previous...
ous reports (Constantinides and Ulm 2007; Jennings 2000; Velez et al. 2001), this article summarizes the indentation modulus ranges of hydration products and pores in Table 4. The percentage of hydration products was shown in Fig. 13(b). Compared with the blank group, as the content of GBFS increases, the content of CH and pores in the paste gradually decreases, which shows that GBFS could fill the pores in the paste. The high indentation modulus (>40 GPa) phase increases with the increase of CS content, indicating that the fayalite in CS does not participate in the reaction, but was filled in the paste as "micro-aggregate". After adding 10% GBFS and 10% CS, the percentage of pores was the lowest, indicating that an appropriate amount of CS could fill the pores. However, when the CS content exceeds 10%, the pore content in the paste increases, indicating that too much CS has a negative impact on the paste structure, resulting in poor abrasion resistance.

3.4.3 SEM and EDS analysis

Figure 14 shows the SEM and EDS image of G10%-CS15% sample. According to the results of points 1, 2 and 3 in the EDS diagram, it could be judged that the SEM image is the ITZ between the aggregate and the paste. In addition, it is found that both points 2 and 3 are fayalite, indicating that CS is mainly used as a filling function in the paste and that fayalite does not participate in the hydration reaction, which is also consistent with the "micro-aggregate effect" mentioned earlier.

3.5 Abrasion resistance mechanism

From the discussion above, it was concluded that when the blending amount of GBFS and CS were both 10%, RAPC has the best abrasion resistance. The mechanism diagram is shown in Fig. 15. The reasons could be revealed from the following aspects:

It is well acknowledged that the effect of GFBS on the abrasion resistance of concrete is complicated. On the one hand, GBFS (D50=3.82 μm) could fill the micropores to compact pore structure; on the other hand, the added GBFS consumes the Ca(OH)2 of hydrated cement, via the pozzolanic reaction, to generate C-S-H gel, enhancing the density of matrix(Alderete et al. 2017). Both of above was resulted in the improvement of RAPC abrasion resistance. In addition, GBFS accelerates the hydration reaction of cement and provides sufficient space for the hydration product, improving the uniformity of the hydration product distribution, which was also positive to improve abrasion resistance (Angulo-Ramírez et al. 2017; Singh et al. 2008). However, the use of GFBS could introduce the extra ITZ, which might be the main reason for the decrease in compressive strength.

Moreover, for CS, it supplied the macro-particles to fill the remaining size pores because CS (D50=63.02 μm) with a large particle size can fill the macropores in the paste to improve the pore structure. The high content of fayalite provided the paste with good abrasion resistance in the form of "micro-aggregates". However, the low pozzolanic activity of CS will seriously affect the compressive strength of RAPC. Moreover, more CS will bring more extra ITZ, resulting in poor abrasion resistance of RAPC.

3.6 Environmental safety assessment

Table 5 shows the results of the leaching concentration of heavy metal ions after testing according to the TCLP standard (Li et al. 2020a). Comparatively, the concentration of all heavy metal ions is far lower than the Class II surface water environmental quality specified in PRC Standard GB 3838-2002, which is consistent with pre
Table 5 Leaching concentration of heavy metal ions in the G10%-CS25% sample compared with the values specified in PRC Standard GB 3838-2002.

| Concentration (mg/L) | Cr  | Mn  | Cu  | Zn  | Pb  |
|----------------------|-----|-----|-----|-----|-----|
| GB 3838-2002         | 0.05| 4.0 | 1.0 | 1.0 | 0.01|
| G10%-CS25%           | N   | 1.0692 | 0.0185 | 0.6482 | 0.0205|

Note: N indicates that the concentration was below the detection limit.

Fig. 14 (a): SEM images of G10%-CS15% sample; (b), (c) and (d): EDS qualitative results for marked spots 1, 2, and 3.

Fig. 15 Mechanism diagram of the improvement of RAPC abrasion resistance.
vious study (Shanmuganathan et al. 2008). This shows that the RAPC fully satisfies the requirements for use and would not cause any environmental safety problems.

When the prepared RAPC is used for road paving, it could not only reduce the environmental pollution of CS from the aspect of raw materials, but also realize the circulation of surface water and groundwater through the pore structure to alleviate urban flood disasters.

4. Conclusions

This work investigated the improvement influence of CS and GBFS on abrasion resistance of RAPC and reveals the mechanism. The main conclusions could be summarized as follows:

1. The incorporation of CS causes the volume of the paste to decrease, resulting in an increase in the porosity and permeability. Owing to the low pozzolanic activity and large particle size of CS, adding significant amount of CS would cause the paste fluidity to be too high. The appropriate rw/c and addition of GBFS would effectively overcome these problems.

2. The addition of GBFS and CS improved the abrasion resistance of the RAPC. When the mass ratios of cement, GBFS and CS in the paste were 80%, 10% and 10%, respectively, RAPC had the best abrasion resistance, which was 38.78% higher than that of the blank group.

3. According to the results of nanoindentation, GBFS and CS could effectively improve the microhardness of the paste. The optimum content of both is 10%, which is consistent with the abrasion resistance test.

4. According to the TCLP standard, the prepared RAPC is environmentally friendly.

5. The conclusions are based on the materials and conditions of this research. The use of other by-products or other types of cements requires new study. Furthermore, durability studies and longterm performance are required before generalization of the results.

Acknowledgements

This work was supported by National Key R&D Plan of China [grant numbers 2019YFC190470301]; and Key R&D Plan of Hubei [grant numbers 2020B0CA077]. The authors would like to thank the State Key Laboratory and Center for Materials Research, Wuhan University of Technology, for material characterization.

References

Al-Jabri, K. S., Taha, R. A. and Al-Ghassani, M., (2002). “Use of copper slag and cement by-pass dust as cementitious materials.” Cement, Concrete and Aggregates, 24(1), 7-12.

Al-Jabri, K. S., Al-Saidy, A. H. and Taha, R. A., (2011). “Effect of copper slag as a fine aggregate on the properties of cement mortars and concrete.” Construction and Building Materials, 25(2), 933-938.

Al-Jabri, K. S., Hisada, M., Al-Saidy, A. H. and Al-Oraimi, S. K., (2009). “Performance of high strength concrete made with copper slag as a fine aggregate.” Construction and Building Materials, 23(6), 2132-2140.

Al-Jabri, K. S., Taha, R. A., Al-Hashmi, A. and Al-Harthy, A. S., (2006). “Effect of copper slag and cement by-pass dust addition on mechanical properties of concrete.” Construction and Building Materials, 20(5), 322-331.

Al-De Belie, N. (2017). “Pore structure description of mortars containing ground granulated blast-furnace slag by mercury intrusion porosimetry and dynamic vapour sorption.” Construction and Building Materials, 145, 157-165.

Aliabdo, A. A., Abd Elmoaty, A. E. M. and Fawzy, A. M., (2018). “Experimental investigation on permeability indices and strength of modified pervious concrete with recycled concrete aggregate.” Construction and Building Materials, 193, 105-127.

Angulo-Ramírez, D. E., Mejia de Gutiérrez, R. and Puertas, F., (2017). “Alkalih-activated Portland blast-furnace slag cement: Mechanical properties and hydration.” Construction and Building Materials, 140, 119-128.

Blutta, M. A. R., Hasanah, N., Farhayu, N., Hussin, M. W., Tahir, M. B. M. and Mirza, J., (2013). “Properties of porous concrete from waste crushed concrete (recycled aggregate).” Construction and Building Materials, 47, 1243-1248.

Bilir, T., Yüksel, I., Topcu, I. B. and Gencel, O., (2017). “Effects of bottom ash and granulated blast furnace slag as fine aggregate on abrasion resistance of concrete.” Science and Engineering of Composite Materials, 24(2), 261-269.

Brake, N. A., Allahdadi, H. and Adam, F., (2016). “Flexural strength and fracture size effects of pervious concrete.” Construction and Building Materials, 113, 536-543.

Cai, L., Li, X., Liu, W., Ma, B. and Lv, Y., (2019). “The slurry and physical-mechanical performance of autoclaved aerated concrete with high content solid wastes: Effect of grinding process.” Construction and Building Materials, 218, 28-39.

Chindaprasirt, P., Hatanaka, S., Chareerat, T., Mishima, N. and Yuasa, Y., (2008). “Cement paste characteristics and porous concrete properties.” Construction and Building Materials, 22(5), 894-901.

Constantinides, G and Ulm, F.-J., (2007). “The nanogranular nature of C–S–H.” Journal of the Mechanics and Physics of Solids, 55(1), 64-90.

El-Hassan, H., Kianmehr, P. and Zouaoui, S., (2019). “Properties of pervious concrete incorporating recycled concrete aggregates and slag.” Construction and Building Materials, 212, 164-175.

Feng, Y., Chen, Q., Zhou, Y., Yang, Q., Zhang, Q., Jiang, L. and Guo, H., (2020). “Modification of glass structure via CaO addition in granulated copper slag to enhance its pozzolanic activity.” Construction and
Building Materials, 240, Article ID 117970.
Gaedicke, C., Marines, A. and Miankodila, F., (2014). “Assessing the abrasion resistance of cores in virgin and recycled aggregate pervious concrete.” Construction and Building Materials, 68, 701-708.
Gao, W., Jian, S., Li, B., Li, X., Tan, H., Huang, W. and Yang, X., (2020). “Solidification of zinc in lightweight aggregate produced from contaminated soil.” Journal of Cleaner Production, 265, Article ID 121784.
Gesoğlu, M., Güneyisi, E., Khoshnaw, G. and Ipek, S., (2014). “Abrasion and freezing-thawing resistance of pervious concretes containing waste rubbers.” Construction and Building Materials, 73, 19-24.
Gorai, B., Jana, R. K. and Premchand., (2003). “Characteristics and utilisation of copper slag - A review.” Resources, Conservation and Recycling, 39(4), 299-313.
He, Z., Chen, X. and Cai, X., (2019). “Influence and mechanism of micro/nano-mineral admixtures on the abrasion resistance of concrete.” Construction and Building Materials, 197, 91-98.
Jennings, H. M., (2000). “A model for the microstructure of calcium silicate hydrate in cement paste.” Cement and Concrete Research, 30(1), 101-116.
Jian, S., Gao, W., Lv, Y., Tan, H., Li, X., Li, B. and Huang, W., (2020). “Potential utilization of copper tailings in the preparation of low heat cement clinker.” Construction and Building Materials, 252, Article ID 119130.
Jiang, D., Li, X., Jiang, W., Li, C., Lv, Y. and Zhou, Y., (2020a). “Effect of tricalcium aluminate and sodium aluminate on thaumasite formation in cement paste.” Construction and Building Materials, 259, Article ID 119842.
Jiang, W., Li, X., Lv, Y., Jiang, D., Liu, Z. and He, C., (2020b). “Mechanical and hydration properties of low clinker cement containing high volume superfine blast furnace slag and nano silica.” Construction and Building Materials, 238, Article ID 117683.
Kajaste, R. and Hurme, M., (2016). “Cement industry greenhouse gas emissions – Management options and abatement cost.” Journal of Cleaner Production, 112, 4041-4052.
Kumar, R., (2017). “Influence of recycled coarse aggregate derived from construction and demolition waste (CDW) on abrasion resistance of pavement concrete.” Construction and Building Materials, 142, 248-255.
Li, B., Jian, S., Zhu, J., Yu, H., Wu, R., Gao, W. and Tan, H., (2020a). “Effect of flux components of lightweight aggregate on physical properties and heavy metal solidification performance.” Waste Management, 118, 131-138.
Li, B., Wang, L., Jian, S., Zhang, J., Gao, W., Zhu, J. and Wu, R., (2021). “Leaching behavior of copper and chromium in the mortar containing artificial fine aggregate prepared by contaminated soil.” Construction and Building Materials, 270, Article ID 121367.
Li, H., Xu, D., Feng, S. and Shang, B., (2014). “Microstructure and performance of fly ash micro-beads in cementitious material system.” Construction and Building Materials, 52, 422-427.
Li, X., He, C., Lv, Y., Jian, S., Liu, G., Jiang, W. and Jiang, D., (2020b). “Utilization of municipal sewage sludge and waste glass powder in production of lightweight aggregates.” Construction and Building Materials, 256, Article ID 119413.
Liu, T., Wang, Z., Zou, D., Zhou, A. and Du, J., (2019). “Strength enhancement of recycled aggregate pervious concrete using a cement paste redistribution method.” Cement and Concrete Research, 122, 72-82.
Lori, A. R., Hassani, A. and Sedghi, R., (2019). “Investigating the mechanical and hydraulic characteristics of pervious concrete containing copper slag as coarse aggregate.” Construction and Building Materials, 197, 130-142.
Ly, C.-Q., Koh, S.-K., Mangabhai, R. and Dhir, R. K., (2015). “Use of copper slag and washed copper slag as sand in concrete: A state-of-the-art review.” Magazine of Concrete Research, 67(12), 665-679.
Ni, T., Ma, W., Yang, Y., Yu, J., Liu, J., Jiang, C. and Gu, C., (2021). “Interface reinforcement and a new characterization method for pore structure of pervious concrete.” Construction and Building Materials, 267, Article ID 121052.
Pan, G., Sun, W., Ding, D. and Zhang, Y., (1998). “Experimental study on the micro-aggregate effect in high-strength and super-high-strength cementitious composites (Communicated by D. M. Roy).” Cement and Concrete Research, 28(2), 171-176.
Panda, S., Sarkar, P. and Davis, R., (2020). “Abrasion resistance and slake durability of copper slag aggregate concrete.” Journal of Building Engineering, Article ID 101987.
Rehder, B., Banh, K. and Neithalath, N., (2014). “Fracture behavior of pervious concretes: The effects of pore structure and fibers.” Engineering Fracture Mechanics, 118, 1-16.
Shanmuganathan, P., Lakshmiopathiraj, P., Srikanth, S., Nachiappan, A. L. and Sumathy, A., (2008). “Toxicity characterization and long-term stability studies on copper slag from the ISASMELT process.” Resources, Conservation and Recycling, 52(4), 601-611.
Shi, C., Meyer, C. and Behnood, A., (2008). “Utilization of copper slag in cement and concrete.” Resources, Conservation and Recycling, 52(10), 1115-1120.
Simmons, C. T., (2008). “Henry Darcy (1803–1858): Immortalised by his scientific legacy.” Hydrogeology Journal, 16(6), 1023.
Singh, S. P., Tripathy, D. P. and Ranjith, P. G., (2008). “Performance evaluation of cement stabilized fly ash-GBFS mixes as a highway construction material.” Waste Management, 28(8), 1331-1337.
Sorelli, L., Constantinides, G., Ulm, F.-J. and Toutlemonde, F., (2008). “The nano-mechanical
signature of ultra high performance concrete by statistical nanoindentation techniques.” *Cement and Concrete Research*, 38(12), 1447-1456.

Tan, H., Deng, X., He, X., Zhang, J., Zhang, X., Su, Y. and Yang, J., (2019a). “Compressive strength and hydration process of wet-grinded granulated blast-furnace slag activated by sodium sulfate and sodium carbonate.” *Cement and Concrete Composites*, 97, 387-398.

Tan, H., Nie, K., He, X., Guo, Y., Zhang, X., Deng, X., Su, Y. and Yang, J., (2019b). “Effect of organic alkali on compressive strength and hydration of wet-grinded granulated blast-furnace slag containing Portland cement.” *Construction and Building Materials*, 206, 10-18.

Torskaya, T., Shabro, V., Torres-Verdín, C., Salazar-Tio, R. and Revil, A., (2014). “Grain shape effects on permeability, formation factor, and capillary pressure from pore-scale modeling.” *Transport in Porous Media*, 102(1), 71-90.

Velez, K., Maximilien, S., Damidot, D., Fantozzi, G. and Sorrentino, F., (2001). “Determination by nanoindentation of elastic modulus and hardness of pure constituents of Portland cement clinker.” *Cement and Concrete Research*, 31(4), 555-561.

Xiao, J., Li, W., Sun, Z., Lange, D. A. and Shah, S. P., (2013). “Properties of interfacial transition zones in recycled aggregate concrete tested by nanoindentation.” *Cement and Concrete Composites*, 37, 276-292.

Yang, L., Kou, S., Song, X., Lu, M. and Wang, Q., (2020). “Analysis of properties of pervious concrete prepared with difference paste-coated recycled aggregate.” *Construction and Building Materials*, 269, Article ID 121244.

Yap, S. P., Chen, P. Z. C., Goh, Y., Ibrahim, H. A., Mo, K. H. and Yuen, C. W., (2018). “Characterization of pervious concrete with blended natural aggregate and recycled concrete aggregates.” *Journal of Cleaner Production*, 181, 155-165.

Yu, F., Sun, D., Hu, M. and Wang, J., (2019). “Study on the pores characteristics and permeability simulation of pervious concrete based on 2D/3D CT images.” *Construction and Building Materials*, 200, 687-702.

Zhang, J., Tan, H., He, X., Yang, W. and Deng, X., (2020). “Utilization of carbide slag-granulated blast furnace slag system by wet grinding as low carbon cementitious materials.” *Construction and Building Materials*, 249, Article ID 118763.

Zhang, J., Tan, H., He, X., Zhao, R., Yang, J. and Su, Y., (2021). “Nano particles prepared from hardened cement paste by wet grinding and its utilization as an accelerator in Portland cement.” *Journal of Cleaner Production*, 283, Article ID 124632.

Zhang, Z., Zhang, Y., Yan, C. and Liu, Y., (2017). “Influence of crushing index on properties of recycled aggregates pervious concrete.” *Construction and Building Materials*, 135, 112-118.