Effect of Waste Glass on Slurry Rheological Properties of Cement and Concrete

Geli Li¹,a*, Youze SHAO¹,b, Yunhui Fang¹,²,c, Weiten Li¹,d, Yanmei LIN¹,e, Dongming YAN²,f

¹KZJ New Materials Co., Ltd., Xiamen 361101, China
²College of Civil Engineering and Architecture, Zhejiang University, Hangzhou 310058, China
ªemail: ligeli2006@kzj.xmabr.com, ²email: 157198689@qq.com, ³email: fangyunhui@126.com, ⁴email: 420249688@qq.com, ⁵email: 547525973@qq.com, ⁶email: 343973635@qq.com
³email: ligeli2006@kzj.xmabr.com

Abstract. In order to realize the recycling of waste glass, the influence of waste glass on the rheological properties of cement paste and concrete was studied. The rheological parameters were obtained by linear fitting with Bingham model. The results showed that for cement slurry system, with the replacement amount of waste glass increasing from 0 wt% to 20 wt%, the plastic viscosity of slurry increased gradually, while the yield stress decreased. Fixing the replacement amount of fixed waste glass at 5 wt%, the plastic viscosity and yield stress of cement slurry decrease with the increasing dosage of polycarboxylate superplasticizer. The cement slurry conforms to the characteristics of pseudoplastic fluid. For initial concrete slurry system, with the increase of waste glass replacement amount from 0 wt% to 20 wt%, the plastic viscosity of slurry increased, while the yield stress gradually decreased. And then the rheological properties of concrete slurry were closed to Newtonian fluid. After 1 hour, the plastic viscosity of concrete increased first, then decreased, and finally increased again. The yield stress decreased gradually. And the rheological properties of slurry were also close to Newtonian fluid.

1. Introduction
The main component of glass is amorphous silica, and the hardness of glass is close to that of ordinary sand [1]. At present, the main disposal method of waste glass is landfill, which has caused a serious environmental pollution problem. The application of waste glass to concrete is a good way to dispose of waste glass, which is of great significance for energy saving, emission reduction and sustainable development [2-3]. The reuse of concrete refers to mainly adding waste glass to concrete as aggregate or auxiliary cementing material. It is usually 28 days after glass frit begins to show certain pozzolanic activity, and it has low water absorption and good durability. Good liquidity and other advantages [4-5]. When glass is used as an aggregate, it will affect the workability and mechanical properties of fresh concrete. The workability is generally evaluated by slump or expansion, and there was very little research on the effect of rheology.

Rheological parameters were important indicators to characterize the fluidity and workability of cement-based materials. In this paper, by studying the changes of the shear stress and apparent...
viscosity of waste glass in cement paste with the change of shear rate, and studying the changed in the rheological behavior of the paste after adding polycarboxylic acid water-reducing agent, finally the concrete rheometer was used to study the influence of waste glass on the rheological behavior of concrete, in order to provide certain theoretical guidance for the recycling and performance evaluation of waste glass.

2. Experiment method

2.1. Main raw materials

(1) Cement (C): P.O 42.5R Minfu cement was selected.
(2) Fly ash (FA): Grade II, the sample was dried without agglomeration, produced by Xiamen Songneng Power Plant.
(3) Slag powder (SL): S95 grade slag powder, produced by Sangang Group (Longhai) Slag Powder Co., Ltd.
(4) Machine-made sand (S): fineness modulus 2.7, mud content 0.8%, produced by Xiamen Xianglian Building Material Co., Ltd.
(5) Waste glass (GG): Produced by Xiamen Tianrun Jinlong Building Materials Co., Ltd.
(6) Stone (G): Continuously graded gravel with a nominal particle size of 10~20 mm, produced by Xiamen Xianglian Building Material Co., Ltd.
(7) Water (W): tap water.
(8) Polycarboxylic acid water-reducing agent (PCE): produced by Kezhijie New Materials Group Co., Ltd., the product model was Point-S04 polycarboxylic acid-based high-performance water-reducing agent, with a solid content of 50%.

2.2. Experiment method

2.2.1. Rheological performance test of cement-based paste
Weigh an appropriate amount of cement, waste glass, and water into the mixing pot and stir with a pure slurry mixer. The mixing procedure is to first stir slowly for 2 minutes, pause for 15 seconds, and then stir quickly for 2 minutes; pour the stirred slurry into 300 mL the beaker, measure the apparent viscosity, shear stress and shear rate of the slurry at different speeds by Brookfield NDJ-8T touch screen viscometer; take the shear stress as the ordinate and the shear rate as the abscissa. Curve fitting, the obtained slope was the plastic.

2.2.2. Concrete rheological performance test
Fresh concrete is designed and tested in accordance with the provisions of GB/T 50080-2016 "Standard for Test Methods for Performance of Ordinary Concrete Mixtures". The German ICAR Plus concrete rheometer was used for the concrete rheology test. Pour the mixed concrete into the rheological bucket, tamping with a tamping rod, gently tap the side of the container with a rubber hammer 10~15 times, and insert the blade into the concrete.

3. Results and discussion

3.1. The effect of different replacement ratios of waste glass on the rheological behavior of cement-based paste
The waste glass was partially replaced by cement, and the influence of different replacement ratios of waste glass on the rheological properties of cement-based paste was investigated. When the replacement ratio of waste glass was 0 wt %, 5 wt %, 10 wt %, 15 wt %, and 20 wt %, they are linearly fitted with the Bingham model, as shown in Table1. The variation of apparent viscosity with shear rate in cement paste with different substitution ratios of waste glass is shown in Figure 1.
Table 1 Rheological fitting equation and correlation coefficient of different replacement amount of waste glass in cement paste

| No. | Fitting equation          | Correlation coefficient | Plastic viscosity/(mPa·s) | Yield stress/mPa |
|-----|----------------------------|-------------------------|---------------------------|-----------------|
| G1  | $\tau = 667.90\gamma + 2145.84$ | 0.9884                  | 667.90                    | 2145.84         |
| G2  | $\tau = 694.26\gamma + 1705.29$ | 0.9886                  | 694.26                    | 1705.29         |
| G3  | $\tau = 710.03\gamma + 1658.95$ | 0.9908                  | 710.03                    | 1658.95         |
| G4  | $\tau = 759.43\gamma + 1578.76$ | 0.9958                  | 759.43                    | 1578.76         |
| G5  | $\tau = 808.19\gamma + 1207.90$ | 0.9885                  | 808.19                    | 1207.90         |

It can be seen from the fitting results in Table 1 that the fitting effect was good, indicating that the rheological curve of the above sample conforms to the Bingham model. As the replacement ratio of waste glass increased, the plastic viscosity gradually increased, and the yield stress gradually decreased. On the one hand, after adding water, the cement-based slurry begins to undergo hydration reaction, forming many flocculation structures, and the frictional resistance between cement particles increased. Slow, indicating that the shear stress destroys the flocculation structure of the cement paste. With the increased of the shear rate, the free water in the paste increased, and the internal friction resistance of the paste decreases. On the other hand, it was because of the water absorption rate of the waste glass. Low, the particle surface was smoother, can play the role of ball, the friction between the particles was reduced, can destroy the flocculation structure of the cement-based slurry, so that the contact points between the cement particles are reduced, and the yield stress was reduced.

Fig. 1 Variation of apparent viscosity of waste glass in cement paste with different replacement amount of waste glass and shear rate

It can be seen from Figure 1 that under the same shear rate, the apparent viscosity of the cement-based slurry changes little with the amount of waste glass replaced; the apparent viscosity decreases with the increase of the shear rate, which is expressed as shear thinning, as the shear rate continues to increase, the apparent viscosity decreases linearly and slowly.
3.2. Influence of different dosages of polycarboxylic acid water reducer on the rheological behavior of cement-waste glass paste

The ratio of waste glass to cement was fixed at 5%, and the effect of different dosages of PCE on the rheological properties of cement-waste glass slurry was investigated. When the content of PCE was 0.1 wt%, 0.15 wt%, 0.20 wt%, 0.25 wt% and 0.30 wt%, the shear stress-shear rate curve using Bingham model for linear fitting to obtain the yield stress and plastic viscosity, as shown in Table 2. The change law of apparent viscosity in the body with shear rate is shown in Figure 2.

| No. | Fitting equation       | Correlation coefficient | Plastic viscosity/(mPa·s) | Yield stress/mPa |
|-----|------------------------|-------------------------|---------------------------|-----------------|
| G6  | $\tau=3614.79\gamma+2762.92$ | 0.9916                  | 3614.79                   | 2762.92         |
| G7  | $\tau=2006.91\gamma+2514.41$ | 0.9985                  | 2006.91                   | 2514.41         |
| G8  | $\tau=616.42\gamma+933.47$  | 0.9991                  | 616.42                    | 933.47          |
| G9  | $\tau=277.47\gamma+621.79$  | 0.9953                  | 277.47                    | 621.79          |
| G10 | $\tau=97.39\gamma+302.94$   | 0.9930                  | 97.39                     | 302.94          |

It can be seen from Table 2 that as the content of PCE increased, the plastic viscosity and yield stress of the slurry system generally show a decreasing trend, and the amplitude gradually decreased. This is because as PCE increased, the flocculation structure of the slurry system can be destroyed, so that the free water in the slurry increased and gradually became thinner, and the plastic viscosity and yield stress of the slurry decrease. However, with the increase of the content, the adsorption of the PCE gradually reaches saturation, and the reduction of the plastic viscosity and yield stress of the slurry becomes smaller.

![Figure 2](image_url)

Fig. 2 Effect of PCE on the apparent viscosity of cement waste glass paste with shear rate

It can be seen from Figure 5 that the apparent viscosity decreases with the increase of the shear rate, which is manifested as shear thinning; as the shear rate continues to increase, the apparent viscosity decreases linearly and slowly; and the low shear rate Next, as the content of PCE increased, the apparent viscosity decreases rapidly.
3.3. The influence of waste glass on the rheological behavior of concrete

Fixed the amount of cement, fly ash, mineral powder, stone and water, using waste glass to replace machine-made sand, and the replacement ratios were 0 wt%, 5 wt%, 10 wt%, 15 wt%, and 20 wt%, respectively. The mixing amount of acid water reducer makes the concrete slump controlled at 220±20 mm, and the expansion degree is 580±30 mm. The concrete mixing ratio was shown in Table 3.

The mixed waste glass was replaced with different proportions of concrete, and the initial slump, initial expansion, slump after 1h loss, and expansion after 1h loss of concrete was tested as shown in Figure 3. The waste glass was used to replace the concrete in different proportions, and the concrete rheological parameters were tested by the Danish ICAR concrete rheometer. The concrete rheological parameters, rheological fitting equations and correlation coefficients are shown in Table 4 and Table 5.

Table 3 Concrete mix proportion (kg/m³)

| No. | C  | FA | SL | S   | GG | G  | W  | PCE |
|-----|----|----|----|-----|----|----|----|-----|
| G11 | 272| 36 | 50 | 820 | 0  | 1009| 175| 1.12|
| G12 | 272| 36 | 50 | 779 | 41 | 1009| 175| 1.10|
| G13 | 272| 36 | 50 | 738 | 82 | 1009| 175| 1.08|
| G14 | 272| 36 | 50 | 697 | 123| 1009| 175| 1.06|
| G15 | 272| 36 | 50 | 656 | 164| 1009| 175| 1.04|

It can be seen from Figure 3 that with the amount of waste glass increased, the amount of PCE decreased from 1.12 to 1.04 kg/m³. Slump, expansion, and the 1h loss slump, expansion had been improved to a certain extent, indicated that the increased waste glass improved the flow properties of concrete. This was mainly because the water absorption rate of glass was lower than that of machine-made sand, which can increase the mixture. At the same time, the glass surface was smoother than machine-made sand, which can reduce the friction and bonding force between the slurry particles, thereby increased the slump and expansion of the mixture.
Table 4 Rheological fitting equation and correlation coefficient of fresh concrete with different replacement amount of waste glass (0 h)

| No. | Fitting equation | Correlation coefficient | Plastic viscosity/(Pa·s) | Yield stress/Pa | Mean square error |
|-----|------------------|-------------------------|--------------------------|-----------------|-----------------|
| G11 | $\tau= 59.07\gamma + 74.69$ | 0.97 | 59.07 | 74.69 | 0.019 |
| G12 | $\tau= 71.22\gamma + 28.92$ | 1.00 | 71.22 | 28.92 | 0.004 |
| G13 | $\tau= 87.09\gamma + 8.21$ | 0.99 | 87.09 | 8.21 | 0.006 |
| G14 | $\tau= 105.46\gamma$ | 0.99 | 105.46 | 0 | 0.019 |
| G15 | $\tau=144.48\gamma$ | 0.96 | 144.48 | 0 | 0.068 |

From the initial experimental data of fresh concrete in Table 4, it can be seen that when the ratio of waste glass to replace machine-made sand is from 0 wt% to 20 wt%, the plastic viscosity of concrete gradually increased, and the yield stress gradually decreased. When the substitution ratio reached 15 wt%, the yield stress decreases to 0; when the substitution ratio reaches 20 wt%, the plastic viscosity reached the maximum value of 144.48 Pa·s. This was mainly because with the gradual increase in the replacement ratio of waste glass with low water absorption and smooth surface, it can overcome the mutual force of the concrete slurry system, and under the action of external shear stress, the interior of the concrete will be severely sheared, make the concrete yield stress decreased, macroscopically manifested as the concrete slump gradually increased, until it decreased to be negligible and not included in the calculation, close to Newtonian fluid. There was no obvious relationship between plastic viscosity and slump.

Table 5 Rheological fitting equation and correlation coefficient of fresh concrete with different replacement amount of waste glass (1 h)

| No. | Fitting equation | Correlation coefficient | Plastic viscosity/(Pa·s) | Yield stress/Pa | Mean square error |
|-----|------------------|-------------------------|--------------------------|-----------------|-----------------|
| G11 | $\tau=79.33\gamma+44.87$ | 0.98 | 79.33 | 44.87 | 0.017 |
| G12 | $\tau=143.36\gamma$ | 0.99 | 143.36 | 0 | 0.014 |
| G13 | $\tau=70.40\gamma$ | 0.98 | 70.40 | 0 | 0.122 |
| G14 | $\tau=100.00\gamma$ | 0.98 | 100.00 | 0 | 0.054 |
| G15 | $\tau=128.81\gamma$ | 0.95 | 128.81 | 0 | 0.061 |

It can be seen from Table 8 that after standing for a period time, the yield stress of concrete G11 without waste glass was 44.87 Pa, while for G12, G13, G14 and G15 with waste glass, the yield stress is reduced to 0. The main reason was that the density difference between the waste glass and the sand and stone aggregates caused the settlement of the denser sand and stone aggregates during the static process of the concrete, which caused the yield stress to be reduced to 0.1h after the loss. With the increase of the glass powder content, the plastic viscosity of the concrete increases first, then decreased, and then increased again.

4. Conclusion
(1) For the cement-based slurry system, as the replacement amount of waste glass increases from 0 wt% to 20 wt%, the plastic viscosity of the slurry gradually increases, and the yield stress gradually decreases; when the replacement amount of waste glass is fixed at 5 wt%, With the increase of the content of polycarboxylic acid water-reducing agent, the plastic viscosity and yield stress of the water slurry decrease, which conforms to the characteristics of pseudoplastic fluid.
(2) For the concrete slurry system, as the replacement amount of waste glass increases from 0 wt% to 20 wt%, the plastic viscosity of the slurry increases, and the yield stress gradually decreases and the rheological properties of the slurry were close to Newtonian fluid; 1 hour loss later, firstly, the plastic viscosity of the concrete increased, then decreased, and finally increased again. The yield gradually decreased, and the rheological properties of the slurry were also close to Newtonian fluids.

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