Effect of Fly Ash Content on Properties of Fibre Reinforced Cementitious Composites

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Abstract. The effects of 20%, 30% and 40% fly ash on the properties of fibre reinforced cementitious composites were studied. The results showed that the fresh slurry changed from shear thinning to shear thickening with the increase of fly ash content. The flexural strength of specimens increased slightly, but the compressive strength of specimens decreased with the increase of fly ash amount. Moreover, the flexural strength of all specimens showed different degrees of shrinkage over time. With the increase of the content of fly ash, the elastic modulus of specimens decreased.

1. Introduction
As the most traditional building material, concrete is widely used in all walks of life. Although ordinary cement concrete has advantages in compression resistance and durability, there are inevitable defects in ordinary cement concrete. The higher the compressive strength of concrete, the greater the brittleness [1-2]. This brings difficulties to the further development and application of concrete. In order to improve the brittleness of concrete and enhance the performance of cement-based materials, the researchers propose to add fibre into ordinary cement concrete to improve the toughness and ductility of concrete. After a period of exploration, Engineered Cementitious Composites (ECC) were first created in 1990s. The invention of ECC not only optimizes the ductility of traditional concrete and breaks through the new field of fibre reinforced concrete, but also shows excellent tensile strain capacity and the ability to control the width of micro cracks with appropriate fibre content (volume fraction ≤ 2.0 %) [3-5]. The ultimate tensile strain of ECC could reach 3%~7%, which is 200~300 times of that of ordinary concrete, which can significantly improve the brittleness and durability of the structure [6]. Over the past years, owing to its outstanding crack-controlling ability, high ductility and excellent tensile strain and self-healing capability, ECC has potentially become a kind of ideal material which was increasingly applied in civil engineering projects, such as for retrofit and repair of highway bridges, and the novel use of ECC as protection cover to improve structural durability, and the results were reported to be favourable [7-8].

As an industrial waste, fly ash (FA) has been successfully used in civil engineering for more than 50 years. It is mainly used as an additive in concrete production to replace Portland cement [9]. FA has pozzolanic activity so that cement-based materials with FA will make secondary calcium-silicate-hydrate (C-S-H) gels by reacting with Ca (OH)2 occurring as a consequence of hydration of the cement, which leads to higher density and strength [10]. Researchers found that fly ash content has an important effect on the mechanical properties of ECC [11-12]. Zhang reported that ECC mixture with fly ash/cement ratio of 4.0 by weight reveals best self-healing effect. The high fly ash content in ECC...
favours its tensile performance under sub-elevated temperature [13-14]. Yu [15] reported that high volume fly ash (FA/C=4.4) ECC can resist a sub-elevated temperature ($\leq$200 °C) exposure, and a moderate temperature treatment ($\leq$100 °C) may actually enhance ECC’s tensile properties. Therefore, FA plays a very important role in the mechanical properties of ECC, and its influence cannot be underestimated, which is worth studying.

Consequently, in order to promote the sustainable development of ECC, a series of comprehensive experimental studies were carried out to study the effect of FA content on the rheological properties, mechanical properties and elastic modulus of ECC.

2. Experimental program

2.1. Material properties

P.O42.5R ordinary Portland cement produced by Sichuan Esheng Cement Group. Sulphoaluminate cement is produced in a factory in Sichuan. Fly ash is grade I fly ash with a density of 2.9g/cm3. Silica fume with SiO2>94% was purchased from a factory in Zibo. The fly ash microbeads with specific surface area of 4030cm2/g were purchased from a factor in Yibin, with a specific surface area of 4030cm2/g. Quartz sand with a maximum diameter of 200 mesh. The fibre is polyvinyl alcohol (PVA) fibre produced by a factory in Anhui. The superplasticizer is ZJ13 with a solid content of 47% produced by China Construction New Materials Co., Ltd.. The mixing water is the tap water of the laboratory. The basic properties of ordinary Portland cement are shown in Table 1. The performance of PVA fibre is shown in Table 2. The appearance of raw materials is shown in Figure 1.

| Table 1. Basic properties of Portland cement |
|---------------------------------------------|
| Density /g cm$^{-3}$ | 3.1 | Specific Surface /cm$^2$g$^{-1}$ | 4110 | Setting Time /min | Initial | Final | 3d | 28d | Flexural Strength /MPa | 5.5 | 8.0 | 28.5 | 50.0 | Compressive Strength /MPa |

| Table 2. Performance of PVA fibre |
|-----------------------------------|
| Tensile strength /MPa | 1230 | Length /mm | 6 | Diameter /μm | 39 | Density /g cm$^{-3}$ | 1.3 | Tensile modulus /GPa | 30.0 |

Figure 1. Appearance of raw materials

2.2. Mixture proportions

The mixture proportions of the specimens are shown in table 3. The water-to-binder ratio of all the ratio designs is 0.2.

| Table 3. The mixture proportions of specimens kg/m$^3$ |
|---------------------------------------------------|
| Compositions | Mix proportion |
| Cement | F20 | F30 | F40 |
| Sulphate aluminium cement | 880 | 757 | 600 |
| Fly ash | 40 | 40 | 40 |
| Silica fume | 262 | 393 | 550 |
| Microbead | 70 | 70 | 70 |
| Microbead | 50 | 50 | 50 |
2.3. Specimen fabrication
In this test, ECC were prepared in a compulsory mixer. The slurry was mixed using a two-step method. In the first step, the dry powder was mixed. In the second step, water reducing agent and water were added. After the slurry was mixed well, the PVA fibre was added into the mixer until the fibre was evenly dispersed. The rheological properties of the mixed slurry were quickly measured, and then specimens of different sizes were formed.

The dimensions of the ECC compression and flexural test specimens are 40mm×40mm×160mm; the elastic modulus specimens are 100mm×100mm×300mm, and the bending specimens are 50mm×10mm×400mm.

The Danish ICAR concrete rheometer was used to test the rheological properties of the freshly mixed slurry. The ICAR rheometer automatically calculated the basic unit Bingham rheological parameters-yield stress and plastic viscosity. Refer to GB/T 17671-1999 "Cement mortar strength inspection method (ISO method)" to test the compressive strength and flexural strength of ECC specimens. Refer to GB/T 50081-2019 "Standard for Test Methods of Physical and Mechanical Properties of Concrete" to test the static compression elastic modulus of ECC specimens.

3. Experimental results and discussion

3.1. Rheological property
Figure 2 showed the rheological properties of freshly mixed slurry. The yield stress of the slurry gradually increased with the increase of the fly ash content, in which the fly ash content increased from 20% to 30%, the slurry yield stress increased by 2.8 times, and the content increased from 30% to 40%, the yield stress of the slurry increased by 4.4 times. It showed that the change of fly ash content has a significant effect on the yield stress of slurry, and the flow velocity of slurry decreases with the increase of fly ash content. This is due to the high-water demand of fly ash affects the distribution of slurry mixing water, which formed a competitive mechanism with the hydrophilicity of the fibre. The enhanced restraint of the fibre to the cement slurry inhibited the flow rate of the slurry, which increased the yield stress of the slurry. It was observed that the viscosity of the slurry changed with the increase of the fly ash content, which first decreased, and then quickly increased to the same level as the original. Among them, the blending amount of 30% is the turning point. When the blending amount is 20%, the slurry expansion degree was small. As the blending amount increased to 30%, the slurry expansion rate increased rapidly. After reaching 40%, the slurry expansion degree decreased sharply. Comprehensive consideration of the yield stress of the slurry indicated that the rheological properties of the slurry develop from shear thinning to shear thickening. The reason is that the hydrophilicity of the fibre and the water demand of the fly ash form a competitive mechanism. The mixing water in the gap was quickly absorbed by the slurry, which increased the consistency of the slurry after shearing. The slurry flow speed and expansion degree were reduced.
3.2. Flexural and compressive strength

The flexural strength of specimens with different fly ash contents is shown in Figure 3.

Figure 3. mechanical properties of specimens

The early stage (3d, 7d) flexural strength of the specimen decreased slightly with the increase of fly ash content, indicating that increasing the amount of fly ash in the system affected the early hydration and energy absorption of the specimen. The ability of the specimen to resist bending load damage at an early stage was reduced. When the amount of fly ash is 20% or 30%, the flexural strength of the specimens decreased at the age of 28d. The larger the shrinkage of the flexural strength with low content. However, the flexural strength of the specimen with 40% fly ash content shrunk at the age of 60 days, indicating that the change in the amount of fly ash affected the development of the flexural strength. This may be due to the decrease in the amount of fly ash in the cementitious material, which enhanced the alkaline environment of the specimen and the fibres are eroded in the alkaline environment. On the other hand, when the fly ash content is increased, the stronger the synergy between the fibre and the matrix, the more energy can be absorbed during the load failure process. The early stage flexural strength of specimens developed faster, and the greater the amount of fly ash, the greater the early stage strength growth rate of the specimen, indicating that the appropriate ratio of fly ash to cement played an important role in the development of the flexural strength. The reason is that the appropriate amount of fly ash could optimize the internal structure of the hardened paste and enhance the strain hardening characteristics of the specimen. The compressive strength of the specimen decreased with the increase of fly ash content, which was due to the slower hydration reaction of fly ash. The compressive strength of all specimens differed greatly at the age of 3 days, especially the specimen with 40.0% fly ash content was only 49.5MPa. But the difference in compressive strength of all specimens was greatly reduced after curing to 7 days. It showed that the
weakening of the early compressive strength of the specimen by fly ash has been greatly improved with the curing age to 7 days.

3.3. Compression ratio and elastic modulus

Figure 4 showed the compression ratio of specimens. It can be seen that increasing the amount of fly ash to 40% in materials system resulted in the largest compression ratio, while compression ratio is relatively small with the fly ash amount of 20% and 30%. It showed that there is a threshold for the amount of fly ash in the materials system. When the amount of fly ash was appropriate, the toughness and ductility of the specimen could be greatly improved. The blending amount of fly ash is 20% and 30%. The 3days compression ratio is smaller than the 7 days compression ratio of the specimens. When the dosage was increased to 40%, the 3days compression ratio of the specimen reached the largest value. As curing age increased, the compression ratio of specimens with fly ash amount of 40% decreased. It showed that the change of the amount of fly ash affected the toughness and ductility of specimens. When the amount of fly ash was low, the peak age of the toughness and ductility increased. This is due to the change in the amount of fly ash affected the hydration process of the cementitious material, which made the development of the compressive and flexural strength of the specimen different.

Figure 5 showed the test result of the elastic modulus. It can be seen that with the increase of the amount of fly ash, the elastic modulus of specimens showed a decreasing trend, indicating that the increase in the amount of fly ash reduced the ability of the specimen to resist elastic deformation. This due to increasing the amount of fly ash improved the toughness and ductility of specimens, so the stiffness decreased.

4. Conclusion

(1) The yield stress of fresh slurry increased continuously, and the viscosity first decreased and then increased with the increase of fly ash content. The slurry developed from shear thinning to shear thickening.

(2) The flexural strength of the specimen increased slightly, but the compressive strength decreased with the increase of fly ash amount. Moreover, the flexural strength of all specimens showed different degrees of shrinkage over time. The shrinkage appeared earlier with the amount of fly ash decreased (≤ 30%).

(3) The content of fly ash had a great influence on the elastic modulus of the specimen. With the increase of the content of fly ash, the elastic modulus of the specimen decreased.

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