Effect of Macro Synthetic Fiber on Mechanical Properties and Flexural Toughness of Nano-scale Admixture Wet-mix Shotcrete

Fengwei Ning*, Yuebo Cai, Jiantong Ding, Yin Bai, Bo Chen and Feng Zhang

Nanjing Hydraulic Research Institute, State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Nanjing, Jiangsu, 210029, China

*Corresponding author’s e-mail: fwning@nhri.cn

Abstract. Mechanical properties and flexural toughness are critical performance representing the supporting ability of shotcrete. Flexural toughness can also be used to evaluate the post-crack performance, which mainly depends on fiber. To further promote the supporting capacity of fiber reinforced Nano-scale admixture shotcrete, four contents of macro synthetic fiber (MSF) including 0.7%, 0.9%, 1.1% and 1.3% in volume percentages were investigated. The results indicated that the compressive strength, tensile strength and flexural strength increased firstly and then decreased as MSF content increasing from 0.7% to 1.3%, of which optimum contents were 0.9%, 0.9% and 1.1% respectively. Increasing MSF content could increase the fiber number in per unit cross-section, which could raise the cooperative bearing capacity of fiber and matrix. Therefore, the mechanical properties were improved. However, once MSF content was too high, fiber coated with cementing paste became poor. The defects and cracks were much easier to be produced because of distance between fibers and boundaries becoming smaller and smaller. Then mechanical properties deteriorated under the interaction of boundary effect and poor dispersion of fibers. Besides, flexural toughness index containing $I_5$, $I_{10}$ and $I_{20}$ was raised with the increase of fiber content, which indicated the improvement of flexural toughness.

1. Introduction

Shotcrete is one of the most critical building materials in supporting construction of underground openings. It can timely keep the surrounding rock stable, and reduce occurrence probability of collapse and rock burst. Recently, with west development strategy pushed on in China, many more underground caverns are built to get through mountains or hills. During the construction process of caverns, wet-mix shotcrete has been playing a very important role in supporting. Especially in bad geological conditions such as rock mass broken zone and weaken surrounding rock zone, the bearing capacity of post-crack shotcrete become much more significant than others. Commonly, steel fiber and steel mesh were added to shotcrete to improve the post-crack bearing performance. However, concrete was rebounded frequently by steel mesh. Steel fiber could increase the friction loss of pipes, and add the probability of pipe blockage when pumping.

In addition, either steel fiber or steel mesh was introduced to shotcrete. Cracks of shotcrete easily occurred because of expansion due to the corrosion of steel. Under such background, macro synthetic fiber (MSF) appeared. It not only improved the compactness and toughness of shotcrete as steel fiber, but also reduced the friction loss of pipes and raised the durability of shotcrete [1]. MSF had a bright future of application in shotcrete.
At the aspect of the study on MSF in shotcrete, Kaufmann et al [2] reported that synthetic fiber displayed lower rebound than steel fiber. Liu et al [3] showed that increasing fiber length could enhance the shear and tensile failure of fibers. Moreover, fiber was the dominant factor on the splitting tensile strength and water permeability. Khooshechin et al [4] pointed out that addition of fiber in shotcrete could reduce the effect of cracking due to shrinkage. Chandramouli et al [5] showed that applying 1.5% of fiber could increase the toughness about 50%, which could prevent the development of more cracks in the concrete. By contrast, there has been much less information available concerning MSF content of shotcrete. Alidoust et al [6] reported that increasing fiber content in specimens improved elastic behavior under dynamic loadings. Tassew et al [7] showed that the compressive strength, flexural strength and shear toughness all increased with the increase of fiber content. Less attention was drawn to the effect of MSF content on the mechanical properties and flexural toughness compared to other properties. A further study still needed to be done.

In this paper, four volume contents of MSF including 0.7%, 0.9%, 1.1% and 1.3% were studied. Compressive strength, tensile strength, flexural strength and flexural toughness were compared with each other to define the optimum MSF content. Besides, mechanism that how fiber content affecting the mechanical properties and toughness was also discussed.

2. Materials and mix compositions

2.1. Materials
An ordinary Portland cement with a fineness of 340m²/kg, a specific gravity of 3.11, and 28-day compressive strength of 53.0MPa was employed. Nano-scale admixture with a fineness of average volume particle diameter of 128 nm, a SiO₂ amount of 82% was used. Manufactured sand of marble rocks crushed with a fineness modulus of 2.8, a stone powder content of 12.5%, a saturated surface-dry water absorption of 1.30% was adopted. Manufactured stone of marble rock crushed with a specific gravity of 2.67, a particle size between 5mm and 15mm was applied. Water reducer was a powder of polycarboxylic acid with a water reducing rate of 26% when 0.1% was added. Accelerator was an alkali-free liquid accelerating agent with a compressive strength rate of 95%, an initial setting time of 3.3 minutes and finial setting time of 8.5minutes when 8% was added. Macro synthetic fiber (MSF) with a length of 30mm and equivalent diameter of 0.81mm, a tensile strength of 474MPa, an elastic modulus of 6.0 GPa, a density of 0.91 kg/m³ was employed.

2.2. Mix compositions
The mix compositions of shotcrete were given in Table.1. There were total four shotcrete mixtures marked as F07, F09, F11 and F13. The MSF contents represented were 0.7%, 0.9%, 1.1% and 1.3% respectively, which were with respect to the total volume of shotcrete.

| Mixtures | Cement | Nano-scale admixture | Sand | Stone | Water | MSF | Water reducer |
|----------|--------|----------------------|------|-------|-------|-----|---------------|
| F07      | 419    | 41.4                 | 1013 | 675   | 201   | 6.4 | 0.46          |
| F09      | 419    | 41.4                 | 1009 | 673   | 201   | 8.2 | 0.46          |
| F11      | 419    | 41.4                 | 1006 | 671   | 201   | 10.0| 0.51          |
| F13      | 419    | 41.4                 | 1003 | 668   | 201   | 11.8| 0.51          |

For each shotcrete mixture, Portland cement was all partly replaced using Nano-scale admixture about 9%. Water to binder ratio was about 0.437. Sand ratio was 60%.

In order to eliminate the effect of air content on mechanical properties and flexural toughness, the constituents and dosage of water reducer were slightly adjusted. As a result, slump up was between 190mm and 210mm. Air content varied from 2.8% to 3.3%.
Accelerator was added to mixtures when they were sprayed to receiving surface. The dosage of accelerator was about 8% of the mass of cementing materials. It was about 36.8 kilograms in one cubic metre shotcrete.

2.3. Methods
Compressive strength, flexural strength, tensile strength and flexural toughness were tested in this study. The specimens were fabricated as follows. Concrete was shot to the steel mould located at an 85-degree angle to the ground plane. Experiments were carried out in laboratory using a wet sprayed machine, of which the air pressure was 0.5MPa, the production efficiency was 6m³/h.

The specimen dimension of tensile strength was 100mm×100mm×515mm, which was fabricated by directly spraying concrete into steel mould of the same dimension. The specimens of other three properties were firstly shot to a steel mould and then cut into specified dimension. The dimension of steel mould referred was 350mm×450mm×120mm. The specimen dimensions of compressive strength, flexural strength and flexural toughness were 100mm×100mm×100mm, 100 mm×100mm×400mm and 100mm×100mm×400mm, respectively.

The tests of compressive strength, flexural strength and flexural toughness were carried out according to DL/T 5721-2015 of Chinese standard (Test code for hydraulic shotcrete). Tensile strength was measured referring to DL/T 5150-2017 of Chinese standard (Test code for hydraulic concrete). The ages for specimens to be tested were all at 28 days.

3. Results and discussions

3.1. Effect of MSF content on mechanical properties of shotcrete
Compressive strength is shown in Figure 1. The results indicated that compressive strength firstly increased and then decreased when MSF content was increased from 0.7% to 1.3%. The optimum content of MSF was 0.9%. The maximum of compressive strength was 49.7MPa. Compressive strengths of other three shotcretes were between 43.9MPa and 44.2MPa, which were decreased about 11% to 12% compared with shotcrete containing 0.9% MSF.

![Figure 1. Results of compressive strength](image-url)

Tong et al [8] carried out similar research using micro synthetic fiber, of which the fiber lengths were 3mm and 5mm, the fiber diameter was 7μm. In the range of 0.1% to 1.0%, the optimum volume content of fiber for compressive strength was 0.5%. Bai et al [9] investigated the effect of steel fiber content on compressive strength. The length and diameter of fiber were 30mm and 0.5mm, respectively. A conclusion could be found that compressive strength of shotcrete was the highest when steel fiber content was 1.5% in the range of 0 to 2.0%. Wang et al. [10] also got similar conclusion with basalt micro synthetic fiber, of which the length was 30mm and the diameter was 15μm. And the optimum content of fiber was 0.1%. On basis of relevant three studies discussed, the tendency could be confirmed that compressive strength firstly increased and then decreased when fiber content was increased. And the optimum volume percentage of micro synthetic fiber was not more than 0.5%. But the optimum content of MSF in this study was 0.9%. The reason was that the diameter of MSF was obviously bigger...
than micro synthetic fiber. Dispersion range of micro synthetic fiber was larger than MSF at the same volume content. Hence, micro synthetic fiber couldn't be uniformly distributed as MSF. Once the content was high enough, it was much easier for micro synthetic fiber to form initial defect, which went against the development of compressive strength.

Besides, during the experimental process of shotcrete under compressive load, transverse tensile strain and transverse tensile stress inevitably occurred. The deformation in the middle part of specimen was higher than two sides due to the constraint of upper pressure plate and lower pressure plate. The failure occurred when the tensile strain surpassed ultimate tensile strain. The failure characteristic of shotcrete without fiber was illustrated in Figure 2 (a). Fiber could pass through the defects or cracks when fiber was introduced to shotcrete, which helped the matrixes in both sides of them connect closely with each other. After that, the unity of shotcrete was strengthened. Cooperative bearing capacity was improved. The characteristics of compressive failure was evidently different from shotcrete without fiber. Many cracks along the transverse direction occurred as was shown in Figure 2 (b). However, once the fiber content was too high, compressive strength deteriorated because fiber coated with paste became poor.

![Figure 2. Characteristics of compressive failure of shotcrete with or without fiber](image)

Tensile strengths of shotcretes with 0.7%, 0.9%, 1.1% and 1.3% of MSF were 3.39MPa, 3.57MPa, 3.43MPa, and 3.43MPa, respectively. It could be seen that tensile strength firstly increased and then decreased when MSF content was increased from 0.7% to 1.3%. The optimum content of MSF was 0.9%. The tendency with respect to fiber content and the optimum content were both the same as that of compressive strength.

Tensile failure was essentially a process of cracks initiation and growth. Initial cracks easily occurred in the interfacial transition zone, which was located between aggregate and cementing paste. In other words, the deterioration behaviour of interfacial transition zone was that arbitrary two aggregates separated from each other. The length of MSF in this study was 30mm, which was about two times or three times of the maximum diameter of coarse aggregates. The fiber could strengthen the connection between arbitrary two aggregates. Especially when fibers were arrayed along the axial direction of shotcrete, the improvement of fiber for tensile strength was the highest. As was known from the fiber spacing theory, increasing fiber content could add the fiber number of per unit cross-section and reduce the average space between fibers, the cooperative tensile performance was enhanced as Figure 3. But when fiber content was further increased, the tensile strength would decrease. There were two main reasons for the decline of tensile strength. On one hand, the distance between the fibers and boundary became smaller with fiber content increased. Then the occurrence probability of defects or cracks was increased. Those could decrease tensile strength, which could be marked as boundary effect. On the other hand, increasing fiber content would result in poor dispersion, which went against fiber coated with cementing paste. Therefore, initial deflects and cracks were formed. The bonding strength among fibers was reduced. As a result, tensile strength was decreased.
Flexural strengths of shotcretes with 0.7%, 0.9%, 1.1% and 1.3% of MSF were 6.40MPa, 6.60MPa, 6.76MPa, and 6.50MPa, respectively. It could be seen that flexural strength firstly increased and then decreased when fiber content was increased from 0.7% to 1.3%. The tendency was similar to that of compressive strength. But the optimum MSF content for flexural strength was 1.1%, which differed from the optimum content of 0.9% for compressive strength and tensile strength. The failure process of shotcrete under flexural load indicated that the warping deformation of shotcrete would be formed when third-point load was applied. The top of shotcrete resisted compressive stress and the bottom of shotcrete resisted tensile stress. It was remarkable that tensile strength was less than one tenth of its compressive strength. Cracks of shotcrete commonly occurred when tensile stress surpassed tensile strength. As was discussed above, fiber could improve the tensile strength of shotcrete. Hence increasing fiber content could promote the flexural strength of shotcrete. The problem that too high fiber content could make a decline in flexural strength existed the same as others. While when fiber content was increased from 0.9% to 1.1%, the positive effect of increasing fiber content was still higher than negative effect. Fiber improving the flexural strength mainly resulted from the improvement of bearing capacity of post-crack shotcrete. The bearing capacity of post-crack shotcrete depended on the number of fibers along the axial direction of shotcrete. That was why the optimum MSF content was 1.1%.

Flexural strength of shotcrete containing 0.7% to 1.3% of MSF were about 6.40MPa to 6.76MPa. Compared with the highest flexural strength of 6.76MPa when fiber content was 1.1%, Shotcrete with higher fiber content or lower fiber content had lower flexural strength. The flexural strength decreased about 2% to 5%. The variation amplitude of flexural strength was smaller than that of compressive strength. The reason was that fibers along the axial direction played major part in improving flexural strength. But not all fibers increased were arrayed along the axial direction due to discreteness caused by shooting process. In other words, only a part of fibers played a role in promoting flexural strength by increasing fiber content. That was why the improvement amplitude of flexural strength was not obvious.

3.2. Effect of MSF content on flexural toughness of shotcrete
Load-deflection curve of flexural toughness test was shown as Figure 4. As was known that fiber changed the brittle fracture characteristics of shotcrete. That was to say, shotcrete had certain bearing capacity after the cracks happened. That was the bearing toughness of post-crack shotcrete.

Flexural toughness index was calculated according to DL/T 5721-2015 of Chinese standard, which was the area under the load-deflection curve up to a certain deflection to the area under the load-deflection curve up to first-crack deflection ratio. The results were illustrated in Figure 5. I1, I10 and I20 were the ratios of the area under the load-deflection curve up to three times, five and a half times, ten and a half times of first-crack deflection to the area under the load-deflection curve up to first-crack deflection respectively. In the range of 0.7% to 1.3%, I5, I10 and I20 were increased with the increment of MSF content. Increasing MSF content could promote the flexural toughness of shotcrete. Taking I20 as an example, the flexural toughness indexes of shotcrete containing 0.9%, 1.1% and 1.3% MSF were enhanced by 1%, 15% and 57% compared with shotcrete containing 0.7% of fibers.
The variation tendency of flexural toughness with the increment of MSF content was different from that of mechanical properties. In the range of 0.7% to 1.3%, the flexural toughness increased all the time with the increment of MSF content, which indicated that the bearing capacity of post-crack shotcrete was promoted. After the matrix cracked, the flexural load was mainly borne by the MSF. During the loading process, the crack opening at the bottom of the concrete increased gradually, and the tensile stress transferred from the bottom of the specimen to the top gradually. The fiber with the same orientation as the axial direction of the concrete and good adhesion between the matrix and its two sides were effective. The greater the number of effective fibers, the stronger the bearing capacity was. The influence of fiber winding and agglomeration on the flexural toughness of shotcrete was less than that of cracking openings. Therefore, the flexural toughness of shotcrete could still be improved by
increasing MSF content when the fiber agglomeration could not significantly weaken the interfacial adhesion.

4. Conclusions
Four contents of macro synthetic fiber containing 0.7%, 0.9%, 1.1% and 1.3% were investigated by measuring compressive strength, tensile strength, flexural strength and flexural toughness. The conclusions were obtained as follows:

The compressive strength, tensile strength and flexural strength of shotcrete increased firstly and then decreased with the increase of macro synthetic fiber content in the range of 0.7% to 1.3%. The optimum fiber contents in shotcrete were 0.9%, 0.9% and 1.1%, respectively.

In the range of 0.7% to 1.3%, flexural toughness index I_s, I_{10} and I_{30} increased with the increase of fiber content, which indicated the improvement of the flexural toughness.

The mechanical properties of wet-mix shotcrete could be improved by increasing the content of macro synthetic fiber, which could increase the number of fibers in per unit cross-section and enhance the cooperative bearing capacity of fibers and matrixes. However, once the content of macro synthetic fiber was too high, fiber coated with cementing paste became poor, and distance between fibers and boundaries becoming smaller. Mechanical properties then deteriorated under the interaction of boundary effect and poor dispersion of fibers.

Acknowledgments
This work was financially supported by National Key research and development plan (Grant No. 2016YFC0401610), National science fund project (Grant No. 51739008) and Natural Science Foundation of Jiangsu Province (Grants No. BK 20181516).

References
[1] Ouyang Y. L., Chen X.J., Lu C.R., et al. (2010) Properties of steel fiber and macro-synthetic fiber reinforced shotcrete. J. Southeast. U: Nat. Sci. Ed., 40:44-48.
[2] Kaufmann J., Frech K., Schuetz P., et al. (2013) Rebound and orientation of fibers in wet sprayed concrete applications. Constr. Build. Mater., 49:15-22.
[3] Liu G. M., Cheng W. M., Chen L. J. (2017) Investigating and optimizing the mix proportion of pumping wet-mix shotcrete with polypropylene fiber. Constr. Build. Mater., 150:14-23.
[4] Khooshechin M., Tanzadeh J. (2018) Experimental and mechanical performance of shotcrete made with Nanomaterials and fiber reinforcement. Constr. Build. Mater., 165:199-205.
[5] Chandramouli K., Rao P. S., Pannirselvam N., et al. (2010) Strength properties of glass fiber concrete. ARPN. J. Eng. Appl. Sci., 5:1-6.
[6] Alidoust P., Keramati M., Shariatmadari N. (2018) Laboratory studies on effect of fiber content on dynamic characteristics of municipal solid waste. Waste Manage., 76:126-137.
[7] Tassew S. T., Lubell A. S. (2014) Mechanical properties of glass fiber reinforced ceramic concrete. Constr. Build. Mater., 51:215-224.
[8] Tong Y., Tian X., zhu C. J., et al. (2015) Experiments and analysis on mechanical strength of carbon fiber reinforced concrete. B. Chin. Ceram. Soc., 34:2281-2285, 2297.
[9] Bai M., Niu D. T., Jiang L., et al. (2013) Research on improving the mechanical properties and microstructure of concrete with steel fiber. B. Chin. Ceram. Soc., 32:2084-2089.
[10] Wang J., Ma Y., Zhang Y., et al. (2014) Experimental research and analysis on mechanical properties of chopped basalt fiber reinforced concrete. Eng. Mech., 31:99-102, 114.