Performance of Steel-Fiber-Reinforced High Performance One-Part Geopolymer Concrete

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The high CO_2 emissions of Ordinary Portland Cement (OPC) production have led to increasing the efforts on developing eco-efficient alternative binders. Geopolymers are inorganic binders proposed as an alternative to OPC, which are mainly based on aluminosilicate by-products and alkali activators. Higher utilization of industrial waste materials, such as ceramic manufacturing waste, could be enabled by geopolymers. In ceramic industry, around 30% of raw materials end up in waste streams, and therefore, an attempt is made to recycle these materials. The ceramic wastes are rich in silicate and aluminate and have therefore high potential to be used in the geopolymeric concrete. In the present paper, the porcelain ceramic waste was used as 10% of total binder weight in substituting ground granulated blast furnace slag (GGBFS). The results showed that the resulting binders have comparatively high compressive strength (≥60 MPa), and show brittle behavior, which is typical to inorganic binders with no fiber reinforcement. Micro steel fibers were used to improve the flexural performance of these binders at three different fibers by mass of binder (0.5%, 1%, and 1.5%). After curing, mechanical performances were investigated by measuring the compressive and flexural strength. The results showed that the addition of steel fibers significantly improved the flexural behavior. In addition, it was revealed that these fiber-reinforced binders had a deflection hardening behavior due to the bridging action of steel fibers.

1 Introduction

Ordinary Portland cement (OPC) contributes significantly to global anthropogenic CO_2 release so that the released carbon dioxide was approximately 5–7% of total global CO_2 in the 2000s [1, 2]. Consequently, the development of alternative low-carbon binders is recognized as an effective alternative to reduce the CO_2 emissions [3,4]. Geopolymers are categorized as a sub-group of alkali-activated binders [5]. These binders are commonly activated by using the alkaline solutions. The impracticalities related to handling large amounts of viscous, corrosive, and hazardous alkali activator solutions have put pressure on developing one-part or "just add water" geopolymers that could be used similarly to OPC-based mixtures [6]. The dry ingredients are mixed with water in one-part geopolymers. Like concrete made from OPC, the plain alkali-activated binders presented a brittle behavior under the submitted loads. Introduction of the fiber improves mechanical properties and reduces the drying shrinkage rate in the reinforced mix compositions. One of the main drawbacks of slag compared to other supplementary cementitious materials is the high drying shrinkage rate, which can be significantly reduced using fibers. Fibers provide a bridging action in the fractured cross section, transferring tensile stresses across the crack. The crack-bridging efficiency of fibers depends on the various parameters such as fiber length, content, and type. Among the fibers, steel fiber was one of the earliest and most effective materials for improving the mechanical properties and impact resistance of cementitious composites [7]. Therefore, short length steel fiber with superior mechanical properties was used to reinforce one-part slag/ceramic based geopolymer mortars [12].

2 Materials and methods

The designed geopolymer mortar composed of GGBFS, ground ceramic waste (porcelain), standard sand and anhydrous sodium silicate (Na_2SiO_3) with a silica modulus of SiO_2/Na_2O= 0.9. Ceramic waste material was provided by IDO-Geberit, Finland, which produces sanitary porcelain. Slag was provided by Finnsementti (Finland). In this study, short length steel fibers with three different contents of 0.5%, 1% and 1.5% (mass of binder) was used to reinforce the mixtures. **Table 1**. lists the physical and mechanical properties of the micro steel fibers. Additionally, porcelain ceramic waste and short length steel fiber used in this experimental study are shown in **Fig. 1a.** and **Fig. 1b.**, respectively. Moreover, the adopted flexural test set up and the fractured surface of the tested specimens are presented in **Fig. 2a.** and **Fig. 2b.**, respectively. **Table 2.** mentions the material proportions of the geopolymeric mixtures.

Table 1: The physical and mechanical properties of short length steel fiber

length to diameter	Elastic modulus (GPa)	Tensile strength (MPa)	Elongation at break (%)	Density (g/cm^3)
333	200	2200	3	7.88

In the batching process of mixtures, the dry ingredients (slag, ceramic waste, anhydrous sodium silicate, and fine aggregates) were mixed for 1 minute. Then, water was added and the obtained mixture was re-mixed for 3 minutes. Finally, the fiber-reinforced mixtures were prepared through gradually adding the fibers to the fresh mixture. Afterward, the mixtures were cast into the prismatic beams (40×40×160

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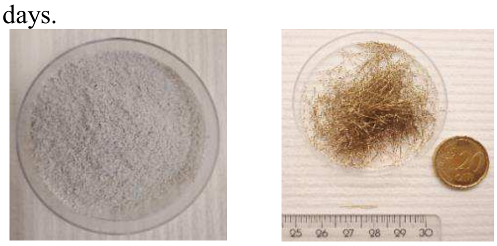
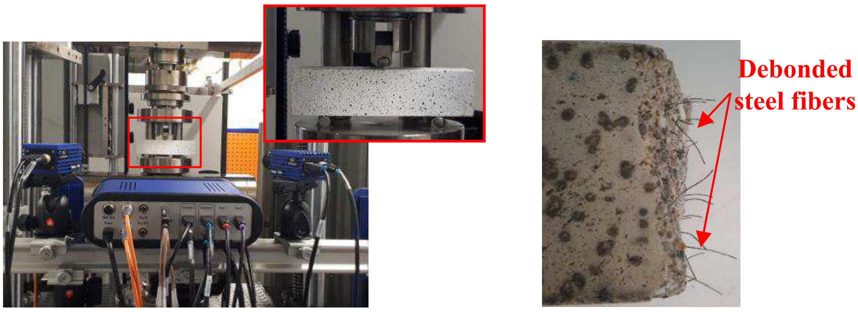
mm) and then specimens were demolded after 24 hours and then covered using the plastic bags for 28 days.



a) b)

Fig. 1: a) Porcelain ceramic waste; b) Used short length steel fiber.



a) b)

Fig. 2: a) Adopted flexural test setup; b) Fractured surface.

Table 2: Mix proportions of one-part slag/ceramic geopolymer

Slag/binder	Sodium silicate/binder	Ceramic waste/binder	Water/binder	Sand/binder
0.80	0.10	0.10	0.35	2.00

3 Test procedures and setups

Twelve prismatic beams with the dimension 40 × 40 × 160 mm were tested to assess the flexural performance of the reinforced and plain beams made with slag/ceramic one-part geopolymers under three-point bending (TPB) test in accordance with the ASTM C78 recommendation [8]. Prismatic beams evaluated under flexural load with a deflection rate of 0.6 mm/min.

Regarding the ASTM C349 recommendation, the compressive strength of mixtures obtained using the portions of prismatic beams broken in the flexure test [9]. The compressive load was measured with a load cell of 100 kN capacity and displacement rate of 1.8 mm/min. The compressive strengths were obtained from averaging six tested specimens.

4 Results and discussion

Fig. 3a. indicates the effects of adding steel fiber on the 28 days compressive strength addition of fiber had no great impact on the compressive strength. The maximum reduction due to introduction of steel fibers was lower than 10%, as compared to the plain mixture. This reduction could be justified by increasing the porosity of the mixture. The minimum and the maximum compressive strengths were recorded around 60 and 65 MPa for the specimens reinforced with 1% and 0% steel fiber, respectively. **Fig. 3b.** represents the influences of adding steel fibers on the flexural strength. The results revealed that the flexural strength was increased consistently by increasing fiber content. The minimum and the maximum flexural strengths were registered about 8.5 and 10 MPa for the specimens reinforced with 0 and 1.5% steel fiber, respectively. Based on the obtained results increasing the amount of steel fiber up to 1.5% resulted in recording about 20% increase of the flexural strength. This improvement was caused by forming hard bond between steel fibers and the embedding matrix, as shown in **Fig. 3c**. the hard bond could be derived from mechanical anchorage of steel fibers, as indicated in **Fig. 3c**. Moreover, the EDS atomic ratios also indicated that C-N-A-S-H gel formed in the matrix, which led to forming a dense matrix. Moreover, **Fig. 2b.** indicates that the steel fibers were dominantly debonded from their surrounded matrix.

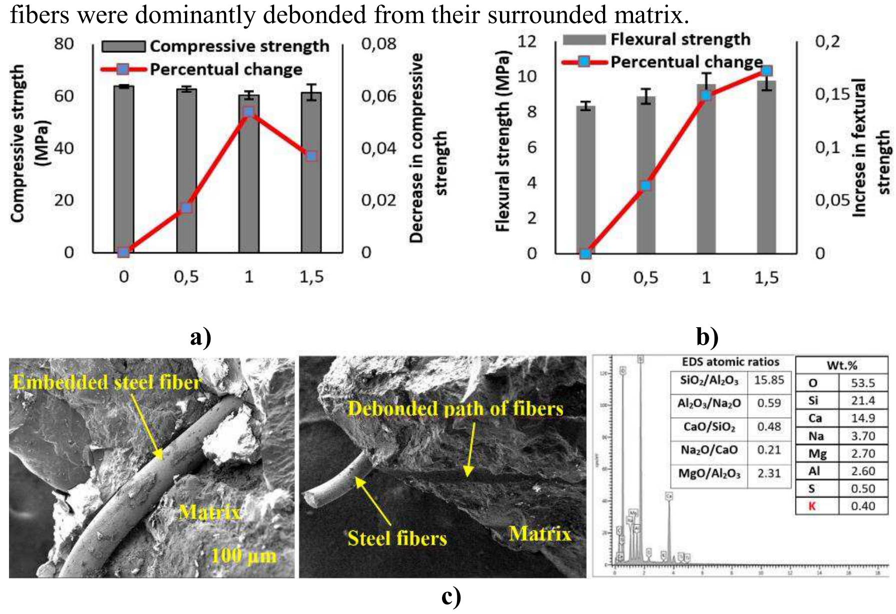


Fig. 3: a) effect of steel fiber on the compressive strength; b) effects of steel fiber on the flexural strength; c) SEM image of the embedded steel fiber into the matrix and EDS analysis of the matrix

It is worth mentioning that previous findings demonstrated that slag/ceramic geopolymers indicated large drying shrinkage compared to other types of geopolymers and this could form some cracks on the surface of specimen, which significantly affects mechanical and durability performances [10-11, 13]. Visual monitoring confirmed that adding fibers controlled the drying shrinkage as no crack was observed on the specimens. Regarding the experimental results, the properties of the mixtures could be correlated through the empirical relations. In order to achieve this aim, the linear regression analysis was used and the empirical relations were developed with high coefficient of determination (R^2= 0.83). **Fig. 4a.** depicts the correlation among the compressive strength, flexural strength, and steel fiber content. With respect to the results, it was observed that the compressive strength was reduced by higher rate than the increase rate of the flexural strength. Moreover, it was revealed that there is a higher correlation between the flexural strength and steel fiber content, when compared to the compressive strength and fiber content. The results in **Fig. 4b.** indicate that there is a linear relation between increasing the flexural strength and decreasing the compressive of the mixtures containing steel fiber, considering a high value of the coefficient of determination (R^2= 0.83).

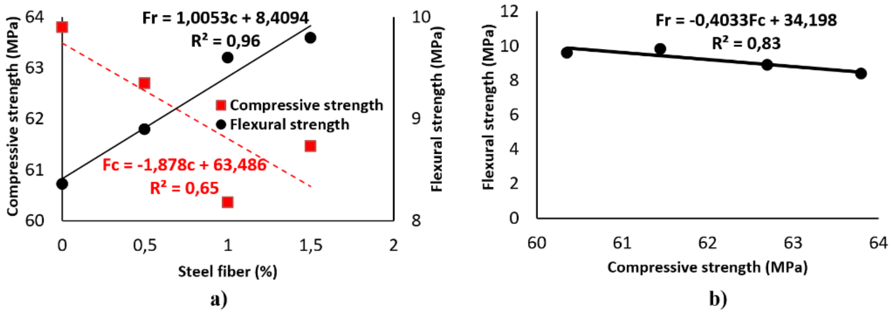


Fig. 4: a) Correlation among the compressive strength, flexural strength, and fiber content; b) Correlation between the compressive and flexural strengths.

In **Fig. 4.**, Fr is the flexural strength, c is fiber content, and Fc is the compressive strength.

5 Conclusions

This paper presents results from an experimental investigation on mechanical performances of the reinforced one-part slag/ceramic geopolymers with short length steel fibers. Mechanical performances was addressed in terms of the compressive and flexural strength. Regarding the results, following remarks could be highlighted:

1. Forming C-N-A-S-H gel provided a dense matrix with reducing the porosity and strengthening the transition zone, which affects the bond properties at the fiber/matrix interface with increasing the friction pull-out behavior.

2. A linear correlation between mechanical characterizations and fiber was found.
3. Higher reduction rate was recorded for the compressive strength due to the addition of steel fibers, as compared to the increase rate of the flexural strength.
4. Regarding the results, the developed geopolymer is amenable to use in practical applications due to acceptable mechanical characterizations. However, further investigations on the durability performance are needed.

6 Acknowledgments

This work was supported by the Finnish Funding Agency for Technology and Innovation (Tekes) [grant number 1105/31/2016] (project GEOBIZ).

7 References

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