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CORRELATION BETWEEN COMPRESSIVE AND TENSILE SPLITTING STRENGTH OF GEOPOLYMER FIBER CONCRETE

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Graphical abstract

Abstract

Geopolymer concrete mixture contain fine and coarse aggregate, fly ash and activator, composed from sodium silicate and sodium hydroxide. Like normal concrete, geopolymer concrete is weak in terms of tensile strength, so fiber needs to be added to improve the mechanical properties of geopolymer concrete. In this research nylon and steel fiber are added to the geopolymer concrete mixture, with percentage from 0.5%, 0.75%, 1%, 1.5% and 2% of volume. The correlation between compressive and tensile splitting strength of geopolymer steel and nylon fiber concrete were evaluated in this research program. The relationship between tensile splitting strength and compressive strength of geopolymer concrete will be built in a mathematical model using multivariable non-linear regression from SPSS software. The specimens are cylindrical concrete, which have diameter of 100 mm and height of 200 mm. The specimen undergo a curing process in an oven at 60°C for duration of 24 hour. Geopolymer concrete mixture with a fiber percentage of 0.75% have a good workability, since they still meet the slump value requirements (10 $\pm$ 2 cm). The compressive strength reaches the highest value at 0.75%, for both steel and nylon fibers. The addition of up to 2% steel fiber produces a splitting tensile strength 12.06% higher than geopolymer concrete with nylon fiber. The equation model proposed for geopolymer fiber concrete is $f_{spt} = 0.049f'_c.\exp(0.7p)$, with the R-square values from 0.722 - 0.715.

Keywords: Geopolymer, nylon fiber, steel fiber, compressive strength, tensile splitting strength

1.0 INTRODUCTION

One of the goals of the Sustainable Development Goals (SDG) is the creation of sustainable cities and communities (SGD11). The development of sustainable urban areas or green cities is carried out by prioritizing the preservation of the natural environment in the all stages of construction process. Therefore, in the process of developing a sustainable city, environmentally friendly materials are needed. Buildings contribute to the total of thirty percent greenhouse gas emissions. Concrete is a construction material that has been used by humans for a long time. Ordinary concrete normally composed from cement, coarse aggregate, fine aggregate and water. However, cement production process can be said to be the largest contributor to CO_2 emissions in the world, which is harmfull to the human life. Nabila *et al.* (2022) stated that the total volume of world cement production in 2016 reached 4174 Mega Tonnes, experiencing a growth of 24.96% from the data in 2010 [1].

Cement factories have a great contribution in CO_2 emission, for about 5 until 7% globally. According to Benhelal *et al*. to produce 1 ton of cement will be able to release 900 kg of CO_2 into the air [2]. The increase of cement production directly increases the amount of CO_2 emissions into the air. Meanwhile, the demand for the development of infrastructure provision in developing countries in the world still relies on reinforced concrete materials made from cement as a base material. This of course requires innovation in terms of providing a sustainable and innovative materials.

One of the innovative steps in the field of concrete materials to reduce the level of emissions from concrete materials is to reduce the use of cement in the concrete mixture. Some alternative materials to substitute cement in concrete mixtures include fly ash, silica fume, rice husk ash etc. These materials can substitute cement up to 100%, meaning the concrete produced is zero cement concrete. This cementless concrete material is often also called geopolymer concrete.

Setiawan *et al*. (2023) proposed a 56.02% reduction of carbon emission, when geopolymer concrete compared to Ordinary Portland Cement concrete (OPC) [3]. The position of cement in the OPC is replaced with cementitious waste materials such as fly ash, which is reacted using an activator solution. The activator generally consists of a solution of sodium silicate or water glass (Na_2SiO_3) and sodium hydroxide (NaOH).

Singh *et al*. (2015) revealed that geopolymer concrete exhibits properties that are not inferior to Ordinary Portland Cement concrete, and has the big opportunity to be used in various concrete-based infrastructure works [4]. Have the same character with OPC concrete, geopolymer concrete also has high compression resistance, but is weak to resist tension force. To increase the tensile strength of geopolymer concrete, efforts can be made by providing additional fillers in the form of fiber.

Some researchers use fibers made from plastic waste [5, 6, 7], hemp [8, 9, 10], bamboo [11, 12, 13], and sisal [14,15,16], or optic fiber [17, 18, 19]. Steel fiber is also quite widely used by previous researchers, such as Akca [20], Brandt [21], Li *et al*. [22], because steel also makes a good contribution to the mechanical properties of concrete.

Akça (2023) stated the increase of concrete tensile strength [20] especially in terms of resistance to cracking and bearing strength, while steel fiber added to the concrete mixture. In addition, steel fibers also have a good ability to resist wear and corrosion. Apart from that, the potential for steel fiber production in Indonesia also supports the use of steel fiber in concrete mixtures. Obtained from the Indonesian Central Bureau of Statistics (BPS) steel fiber production in Indonesia in 2019 reached around 476 thousand tons, an increase from the previous year's production of around 459 thousand tons. However, even though steel fiber has the potential to be used, this material is expensive and has an impact on increasing overall concrete manufacturing costs.

Apart from the materials above, a plastic-based fiber that also has the potential to be used in concrete mixes is nylon fiber. Ahmad *et al*. [7] stated that the addition of 1.5% nylon fiber can improve durability and increase the mechanical properties of concrete, especially its split tensile strength.

Korniejenko (2020) stated that until now, researchers have found that there is still a big opportunity to use fiber in geopolymer concrete [23]. However, research on the use of fiber in geopolymer concrete still needs to be investigated further, especially its function in improving the mechanical properties of geopolymer concrete. This research has an objective to investigate the correlation between compressive and tensile splitting strength of geopolymer steel and nylon fiber concrete. The relationship between tensile splitting strength and compressive strength of geopolymer concrete will be built in a mathematical model using multivariable non-linear regression from SPSS software.

2.0 METHODOLOGY

The object of this research is geopolymer concrete made from fly ash which is reinforced with fiber as an additive. Fibers used in this research are nylon fibers and steel fibers, which have 30 mm in length and 0,6 mm in diameter, so the ratio of length to diameter (L/D) is equal to 50. Geopolymer concrete consists of a mixture of fly ash, alkaline solution (NaOH and Na_2SiO_3), coarse aggregate (*gravel*), fine aggregate (*sand*), and addition water as a solvent for NaoH. Table 1 provide the physical properties of coarse and fine aggregate used in this research.

Table 2 provide the chemical content of fly ash material in percentage. From the results of the XRF examination, the composition of SiO_2 + Al_2O_3, + Fe_2O_3 which is owned by the fly ash material is 81.8%, based on these data the fly ash in this study is fly ash class F, according to ASTM C 618.

Table 1 Aggregate properties

Properties	Coarse Aggregate	Fine Aggregate
Specific gravity	2.53	2.53
Unit weight	1.45	1.45
Organic impurities (%)	0.85	3.64
Absorption (%)	2.65	2.78
Fineness Modulus	7.77	3.24
Abrasion Resistance (%)	18.92	

Table 2 Chemical content of fly ash by XRF test

Chemical composition	%	Chemical composition	%
SiO_2	41.4	P_2O_5	0.4
Al_2O3	22.7	MnO	0.3
Fe_2O_3	17.7	Si	19.3
CaO	8.7	Fe	12.4
MgO	4.5	Al	12
Na_2O	1.1	Ca	6.2
SO_3	1	Mg	2.7
TiO_2	1	Others	2.9
K2O	0.7		

The specimens to be used in this study were cylindrical specimens measuring 10 cm × 20 cm. Variations in the percentage of addition of nylon fiber and steel fiber to the geopolymer concrete mix were taken at 0.5%, 0.75%, 1%, 1.5% and 2%. The percentage of fiber quantity is calculated on the cement weight, referring to the research results of Ahmad *et al*. [7] which stated that the addition of 1.5% nylon fiber can improve durability and increase the compressive strength value of concrete. Mix design of the geopolymer concrete is presented in Table 3. The NaOH molarity taken at 8M.

Standard Used

Testing of the mechanical properties of geopolymer concrete was carried out at 7, 14 and 28 days after the specimen was casted. The following ASTM standard were used to conduct the mechanical properties test of the specimens.

1. ASTM C192/C192M-15 Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory
2. ASTM C39/C39M-21 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens
3. ASTM C496-96 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens.

Mixing Process

The process of making geopolymer concrete test specimens refers to ASTM C192/C192M-15 Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory by modifying the process and implementation time. In general, the implementation of making specimens is carried out using the following process:

1. Weigh and prepare the material according the composition shown in Table 3.
2. Dilute solid NaOH using water, until it reaches a molarity of 8M, this process takes 2 minutes
3. Mix the NaOH 8M solution with the Na_2SiO_3 solution to become the activator solution, this process lasts for approximately 3 minutes.
4. Mix the activator solution with fly ash, stir for approximately 5 minutes until it becomes geopolymer paste
5. Mix the geopolymer paste with coarse and fine aggregate until it becomes a homogeneous geopolymer concrete mix
6. The concrete mixture is molded into a concrete cylinder mold and after 24 hours the specimen undergoes an ovening process at 80°C for 4 hours.
7. Place the specimens at room temperature for 1 day, then soak it in a water bath for 28 days until the test object is ready to undergo mechanical properties tests.

Several previous studies have developed concrete mix design models using the regression method [27-31]. The model developed by previous researchers was used to obtain a relationship between the mechanical properties of concrete (compressive strength) and the independent variables in the form of the basic ingredients that make up concrete. The models that have been proposed previously are linear with limited accuracy. However, Ruoyu, J. *et al* [32] proposed another model using non-linear and mixed regression, the results obtained showed that the model had better accuracy values.

In this research program, the relationship between tensile splitting strength and compressive strength of geopolymer concrete will be built in a mathematical model using multivariable non-linear regression. The basic equation model takes an exponential function in the form

$$f_{spt} = A.f'_c.\exp(B.p) \quad (1)$$

where A and B are constants. As independent variables in the equation, are the parameters f'_c (compressive strength of geopolymer concrete, MPa), and p (percentage of fiber in the concrete mixture, in %). Meanwhile, f_{spt} acts as the dependent variable, which is the splitting tensile strength of geopolymer concrete (MPa). The model was analyzed using SPSS v27 software.

Table 3 Mix design of geopolymer fiber concrete (in kg/m³)

Code	% Fiber	Fly Ash	Na2SiO3	NaOH	Water	Gravel	Sand	Nylon	Steel
GP0	0.0%	431.82	161.93	53.98	40.21	1166.75	590.32	-	-
GPNF1	0.5%	431.82	161.93	53.98	40.21	1166.75	590.32	0.009	-
GPNF2	0.75%	431.82	161.93	53.98	40.21	1166.75	590.32	0.013	-
GPNF3	1.0%	431.82	161.93	53.98	40.21	1166.75	590.32	0.018	-
GPNF4	1.5%	431.82	161.93	53.98	40.21	1166.75	590.32	0.027	-
GPNF5	2.0%	431.82	161.93	53.98	40.21	1166.75	590.32	0.036	-
GPSF1	0.5%	431.82	161.93	53.98	40.21	1166.75	590.32	-	0.062
GPSF2	0.75%	431.82	161.93	53.98	40.21	1166.75	590.32	-	0.092
GPSF3	1.0%	431.82	161.93	53.98	40.21	1166.75	590.32	-	0.123
GPSF4	1.5%	431.82	161.93	53.98	40.21	1166.75	590.32	-	0.185
GPSF5	2.0%	431.82	161.93	53.98	40.21	1166.75	590.32	-	0.246

Concrete cylinder specimens that have been printed are stored for 24 hours at room temperature (16°C - 27°C), while maintaining humidity stability. To help the geopolymerization process run perfectly, the concrete is cured using oven at a temperature of 60 for 24 hours. Concrete curing in the oven is carried out 24 hours after the test object is cast. Figure 1 shows the curing process of geopolymer concrete cylinder.

Figure 1 Curing process of geopolymer concrete using oven at 60°C for 4 hours

3.0 RESULTS AND DISCUSSION

The parameters observed in this research activity including the slump value of concrete mixture, compressive and tensile splitting strength of geopolymer fiber concrete, at the ages of 7, 14 and 28 days.

3.1 Slump Test Value

Slump is basically a simple test to identify the workability of concrete mixture. Workability of fresh concrete is generally associated with homogeneity, cohesiveness, flowability and plasticity of fresh concrete. Method to determine the slump value of concrete mixture is based on ASTM C143/C143M-12. Figure 2 provide slump test results of two types of geopolymer concrete mixtures, namely a mixture of geopolymer concrete with nylon fiber and a mixture with steel fiber.

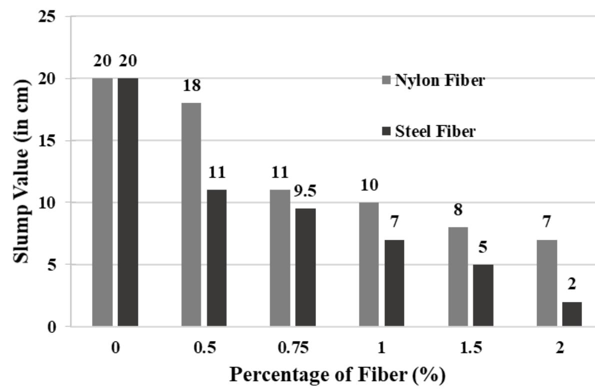

Figure 2 Slump value of fiber geopolymer concrete

Based on the test results for the slump value shown in Figure 2, it can be seen that the geopolymer concrete mixture without fiber (0%) shows a fairly good slump value, equal to 20 cm. This value is higher than the planned slump target (10 ± 2 cm). The slump value decreases as the volume of fiber added to the mixture increases. Geopolymer concrete with steel fiber tends to produce a smaller slump value than nylon fiber. With a target slump value for the geopolymer concrete mixture of 10 ± 2 cm, a mixture with a fiber percentage of 0.75% still meets the slump value requirements. Increasing the fiber volume up to 2% reduces the slump value by 65% (for nylon fiber) and 90% (for steel fiber).

Abdullah *et al*. [24] obtain the same result, which stated that geopolymer concrete with 7% hooked steel fiber experienced a decrease in slump value of up to 70% compared to geopolymer concrete with 0% fiber. Other research on the slump value of geopolymer concrete using Nylon66 fiber [25], also shows a decrease in the slump value of 34.5% with the addition of up to 2% nylon fiber. These results prove that the addition of fiber generally makes a negative contribution to the workability of geopolymer concrete mix. Friction between the aggregate and steel or nylon fibers increased the viscosity of the concrete mixture, and decreased the slump value of the concrete mixture. Concrete with nylon fibers show better slump values than steel fibers. This is possible because the surface of nylon fiber is smoother than steel fiber, so the viscosity of the mortar with nylon fiber is also lower than that of steel fiber.

3.2 Compressive Strength

The growth in compressive strength values of geopolymer concrete with nylon fiber and steel fiber respectively are shown in Figure 3 and Figure 4. From the results of compressive strength test of geopolymer concrete with nylon fiber and steel fiber, in general both mixtures show an increase in compressive strength as the age of the test object increases. Maximum compressive strength is achieved at 28 days of age. In general, geopolymer concrete mixtures with the addition of up to 0.75% fiber are able to exceed the targeted compressive strength of 35 MPa. The GPNF2 mixture with 0.75% nylon fiber was able to achieve 39.95 MPa (14.13% above the design compressive strength). This result is higher than the research results of Yazid *et al*. [25] which only shows an increase in compressive strength of up to 3.74% with nylon 66 fiber. The GPSF2 mixture with 0.75% steel fiber was able to reach 40.39 MPa of compressives strength (15.39% above design compressive strength). This result is quite close to the results obtained by Abdullah *et al* [24] which showed an increase in compressive strength of up to 15.9% with the addition of steel fiber up to 1%. Fiber content up to 2% tends to reduce the compressive strength value of concrete by 19.91% (GPNF5) and 14.87% (GPSF5).

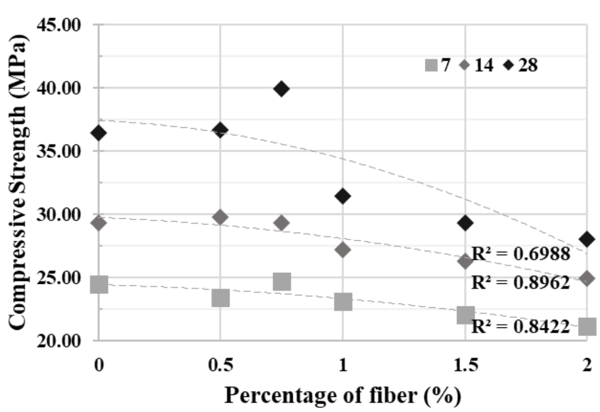

Figure 3 Compressive strength test of geoplymer concrete with nylon fiber

Meanwhile, the growth rate of compressive strength of geopolymer concrete at the ages of 7 and 14 days shows a growth rate that is almost the same as normal concrete. Geopolymer concrete with steel fiber at 7 days and 14 days can reach 71% and 86% of 28 days compressive strength respectively. Meanwhile, geopolymer concrete with additional nylon fiber was able to reach 69.52% compressive strength at 7 days, and 83.37% at 14 days.

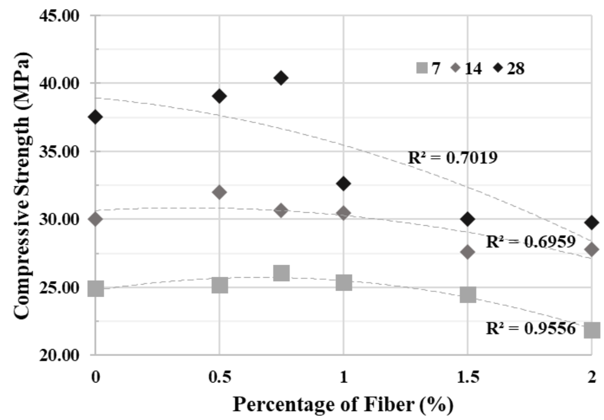

Figure 4 Compressive strength test of geoplymer concrete with steel fiber

Figure 5 shows a comparison of 28 day compressive strength values between concrete with additional materials of nylon fiber and steel fiber for various percentage of fiber. From Figure 5, it can be seen that for all variations in the percentage of fiber content, the mixture using steel fiber as additional material shows a relatively higher compressive strength value than the mixture with nylon fiber, with an average difference of 3.67% higher. The compressive strength value as explained previously reaches the highest value at 0.75%, for both steel and nylon fibers.

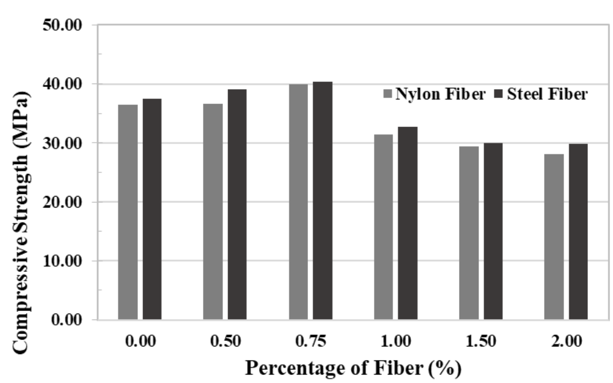

Figure 5 Comparison of 28th days compressive strength between nylon and steel fiber

3.3 Tensile Splitting Strength

Figure 6 provide comparison of the splitting tensile strength values of geopolymer concrete with nylon fiber and steel fiber. The more fiber add to the geopolymer concrete mixture the higher the splitting tensile strength of the concrete. From the test result, concrete tensile strength increase linearly as a function of the steel fiber volume fraction was observed. The same result showed by Maksum *et al*. [26], which shows an increase in split tensile strength of up to 162.16% with the addition of 2% steel fiber.

In general, geopolymer concrete with steel fibers shows higher split tensile strength values than geopolymer concrete with nylon fibers. The addition of up to 2% steel fiber produces a splitting tensile strength of 6.50 MPa, 12.06% higher than geopolymer concrete with nylon fiber (5.80 MPa). On average, the geopolymer concrete with the addition of steel fiber shows a higher tensile splitting strength value of around 4.78% than geopolymer concrete with nylon fiber.

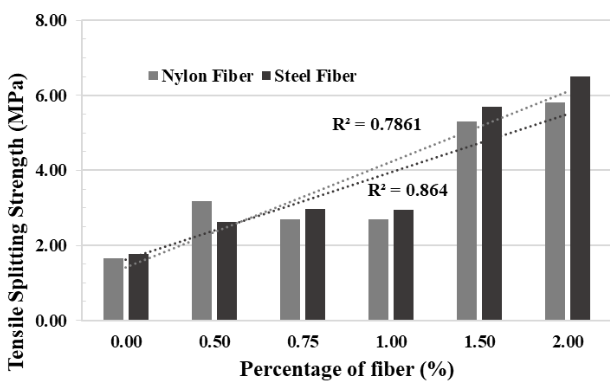

Figure 6 Comparison of 28th days tensile splitting strength between nylon and steel fiber

3.4 Correlation between Tensile Splitting Strength and Compressive Strength

From the results of multi-variable non-linear regression analysis, the regression relationship for both nylon and steel fiber is $f_{spt} = 0.049.f'_c.\exp(0.7p)$. The *R*-square values for the nylon fiber and steel fiber geopolymer concrete models are 0.722 and 0.715 respectively. Figure 7 shows the plotting between the real f_{spt} value and the prediction of f_{spt} value from the model.

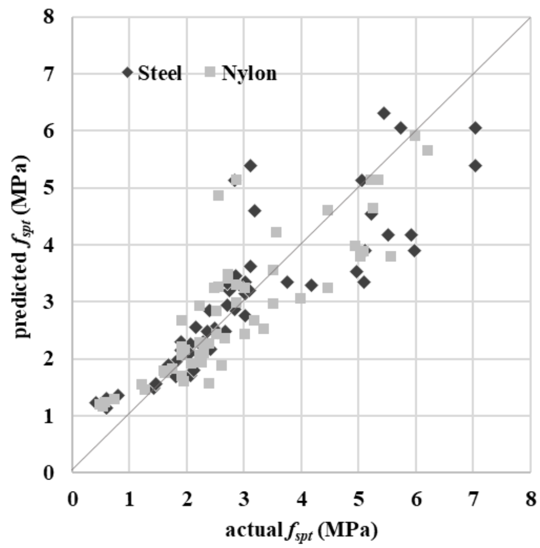

Figure 7 Plotting actual f_{spt} and predicted f_{spt} of fiber geopolymer concrete

4.0 CONCLUSION

Geopolymer concrete mixture with a fiber percentage of 0.75% have a good workability, since they still meet the slump value requirements (10 ± 2 cm). Increasing the fiber volume up to 2% reduces the slump value by 65% (for nylon fiber) and 90% (for steel fiber). The compressive strength value as explained previously reaches the highest value at 0.75%, for both steel and nylon fibers. In general, geopolymer concrete with steel fibers shows higher split tensile strength values than geopolymer concrete with nylon fibers. The addition of up to 2% steel fiber produces a splitting tensile strength 12.06% higher than geopolymer concrete with nylon fiber. The equation model proposed for geopolymer fiber concrete is $f_{spt} = 0.049f'_c.\exp(0.7p)$, with the *R*-square values from 0.722 - 0.715.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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