Arch. Metall. Mater. **67** (2022), 1, 261-267

DOI: https://doi.org/10.24425/amm.2022.137500

MEOR AHMAD FARIS[1,2*], MOHD MUSTAFA AL BAKRI ABDULLAH[1,3], RATNASAMY MUNIANDY[4], SHAMALA RAMASAMY[1,2], MOHAMMAD FIRDAUS ABU HASHIM[1,2], SUBAER JUNAEDI[5], ANDREI VICTOR SANDU[6], MUHAMMAD FAHEEM MOHD TAHIR[1,3]

REVIEW ON MECHANICAL PROPERTIES OF METAKAOLIN GEOPOLYMER CONCRETE BY INCLUSION OF STEEL FIBERS

This study summarised the recent achievement in developing fiber reinforced geopolymer concrete. The factor of replacing Ordinary Portland Cement (OPC) which is due to the emission of carbon dioxide that pollutes the environment globally is well discussed. The introduction towards metakaolin is presented. Besides, the current research trend involved in geopolymer also has been reviewed for the current 20 years to study the interest of researchers over the world by year. Factors that contribute to the frequency of geopolymer research are carried out which are cost, design, and the practicality of the application for geopolymer concrete. Besides, the importance of steel fibers addition to the geopolymer concrete is also well discussed. The fundamental towards metakaolin has been introduced including the source of raw material, which is calcined kaolin, calcined temperature, chemical composition, geopolymerisation process, and other properties. Alkali activators which are mixing solution between sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) have been reviewed. The mechanical properties of fibers reinforced metakaolin-based geopolymer concrete which is compressive and flexural are thoroughly reviewed. The compressive and flexural strength of fiber-reinforced metakaolin geopolymer concrete shows some improvement to the addition of steel fibers. The reviews in this field demonstrate that reinforcement of metakaolin geopolymer concrete by steel fibers shows improvement in mechanical performance.

Keywords: geopolymer; metakaolin; fiber reinforced concrete; steel fibers; mechanical properties

1. Introduction

Concrete is the most useful material used in construction sites globally as it is low cost. The concrete is made by cement, but carbon dioxide will be released in the process of making cement. It is said that around 7% of carbon dioxide is produced during the process of manufacturing cement [1]. The tensile strength of the concrete is relatively low when it is compared to compressive strength which may restrict the uses of the concrete [2]. In this new modern era, cement is replaced by another material which is called geopolymer concrete to reduce the problem of emission of carbon dioxide. By comparison to the application of cement, it is said that the application of geopolymer could reduce the emission of carbon dioxide by 64% [3]. The coarse and fine aggregates that bind together with the geopolymer will produce the concrete [4]. Geopolymer has a similarity with ordinary Portland cement (OPC) which is low in tensile strength with brittle characteristics, and crack under low mechanical loading [5,6].

Geopolymer is an inorganic polymer that has good bonding properties. Besides, geopolymer requires the source materials to undergo the reaction of polymerisation which is aluminosilicate material and alkaline activated solution [3]. The source materials such as fly ash, metakaolin, slag, and rice husk ash are used for polymerisation process to generate polymer binder. The process of polymerisation is involved in the mixture of silica (Si) – alumina (Al) which creates a three-dimensional polymeric chain of Si-O-Al-O bonds [7]. Natural materials or by-products could be used to generate geopolymer as long as the material itself contains Si and Al. According to the study, it is reported that fly ash and metakaolin contain sodium aluminosilicate [7]. Moreover, it is found that metakaolin-based geopolymer has more persistent

---

[1] UNIVERSITY MALAYSIA PERLIS, FACULTY OF CHEMICAL ENGINEERING TECHNOLOGY, CENTER OF EXCELLENT GEOPOLYMER AND GREEN TECHNOLOGY, PERLIS, MALAYSIA
[2] UNIVERSITY MALAYSIA PERLIS (UNIMAP), FACULTY OF MECHANICAL ENGINEERING TECHNOLOGY, PERLIS, MALAYSIA
[3] UNIVERSITY MALAYSIA PERLIS (UNIMAP), FACULTY OF CHEMICAL ENGINEERING TECHNOLOGY, PERLIS, MALAYSIA
[4] UNIVERSITY PUTRA MALAYSIA, DEPARTMENT OF CIVIL ENGINEERING, SELANGOR, MALAYSIA
[5] UNIVERSITAS NEGERI MAKASSSAR, FACULTY OF MATHEMATICS AND NATURAL SCIENCES, INDONESIA
[6] GHEORGE ASACHI TECHNICAL UNIVERSITY OF LASI, FACULTY OF MATERIALS SCIENCE AND ENGINEERING, LASI, ROMANIA

* Corresponding author: meorfaris@unimap.edu.my

properties compared to the other based geopolymer like fly ash-based geopolymer and slag-based geopolymer.

The research trend for the geopolymer concrete in the 20 years which is from 2001 to 2020 is constructed in Figure 1 [8]. The graph shows research on geopolymer concrete is gradually increase from year to year and increase dramatically starting in 2011 until 2020. The frequency for the geopolymer is influenced by three factors which are the cost, design, and the practicality of application of geopolymer concrete. The price of the geopolymer concrete plays an important role as it must be reasonable and it may be competitive with the other types of materials. The design of the geopolymer concrete element is also another reason which affects the uses of geopolymer concrete in the market. Besides, the practice of application of geopolymer concrete requires more reliable data for support.

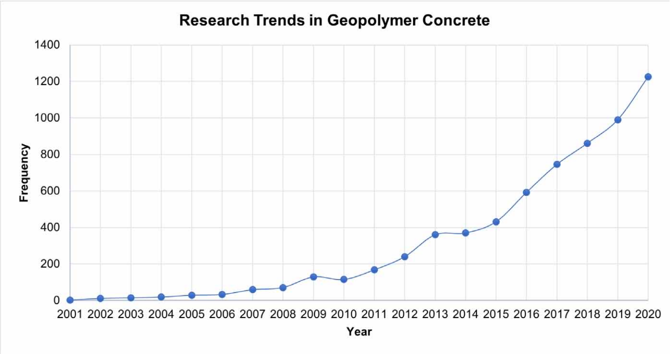

Fig. 1. Summary of research trend involved in geopolymer concrete from 2001 to 2020 [8]

Metakaolin is commonly used to produce ceramics but it is also used as the replacement of cement in concrete as it is more environmentally friendly. Besides, metakaolin can help to enhance the properties of mortar and concrete. Furthermore, metakaolin is produced by the utilization of calcined clay which comes from the calcination of kaolin clay. Suitable treatment is carried out to convert kaolin into metakaolin [9]. Metakaolin can be used as a source of alkali-activated or cemented materials in geopolymers.

Concrete is known as a brittle material that has a low tensile stress resistance and cracks propagation. Steel fibers are commonly used in cementitious composites because of their high mechanical strength and flexibility [5]. By mixing the steel fibers into the concrete could help to increase the tensile strength, ductility, impact resistance, crack resistance, load-bearing capacity, and also fracture energy absorption [9,10]. When the concrete starts to crack, it will first reflect on the fiber instead of the concrete body. The types of fiber will influence the workability of the mixture of fresh fiber. The crimped types of fiber such as rectangular and circular will only yield slightly higher slumps. It is reported that hooked steel fiber is more effective than both the straight types and crimped types of fiber in the flexural and compressive strength of concrete [9]. The effect of the hooked steel fibers addition on metakaolin-based geopolymer concrete will be discussed in detail.

2. Steel Fiber Reinforced Metakaolin Geopolymer Concrete

Metakaolin. Metakaolin is produced by a thermal treatment named calcination. Metakaolin undergoes a calcination process of kaolinite at a temperature between 700°C to 850°C by dihydroxylation where the water is driven off from the kaolinite ($Al_2O_3.2SiO_2$) [11]. Metakaolin is potentially used as a substitute material for ordinary Portland cement as they are excellent in their properties such as thermal stability and acid resistance. The source of silica and alumina which can be dissolved in the alkaline solution is called activated solution which can act as the geopolymer precursor [12]. Based on the study, the inclusion of metakaolin and steel fiber will greatly influence the mechanical properties of the concrete. The workability of metakaolin based concrete is better than silica fume-based concrete in the term of strength [9]. The normal chemical properties of metakaolin are listed in Table 1 [13].

TABLE 1

Chemical composition of metakaolin [13]

Composition	Result (%)
SiO_2	54.00
Al_2O_3	31.70
TiO_2	1.41
Fe_2O_3	4.89
ZrO_2	0.10
K_2O	4.05
Na_2O	2.32
MnO	0.11
L.O.I	1.41

Researchers tend to produce metakaolin from kaolin instead of using ready-made that available on market. This is due to the metakaolin that is available in the market is normally made for a specific purpose which is not suitable to be used as a precursor in geopolymer production. For example, Yunshenget al. calcined China kaolin at a temperature of 700°C for 12 hours [14]. Meanwhile, Kenne et al. calcined Cameron kaolin using a different method in which they heat it up at 105°C for a week until the mass of kaolin becomes constant. The particle size of metakaolin produced was 14 µm. After that, the kaolin was ground and sifted by using a sieve of mesh 90 µm. Then, the dried kaolin was calcined for 30 minutes at 700°C with various calcination rates which are 1, 2.5, 5, 10, 15, and 20 K/min [15]. Meanwhile, Rovnanik produced metakaolin geopolymer through the calcination of Czech Republic kaolin at 750°C in a rotary kiln [16]. Rowles and O'Connor calcined Australian kaolinite at 750°C in the air for 24 hours [17]. Zhue et al. calcined Fujian kaolin at a temperature of 750°C for 2 hours and produced a particle size of about 8 µm of metakaolin [18]. There are researchers produced metakaolin geopolymer by heating at a higher temperature which is Zhang et al. where China kaolin was calcined at 900°C and produce 17 µm of particle size [19]. There was a limited study of metakaolin geopolymer reported using commercialized metakaolin and one of the researchers was Zhao et al where commercial China Metakaolin was used as a precursor [20].

Alkali Activator. The main constituents of geopolymers contain alkali-activated solutions which are very important for the formation of Aluminium (Al) and Silicon (Si) crystals and are commonly based on solvent alkali metals solution. NaOH or KOH and Na_2SiO_3 or K_2SiO_3 are the types that are widely been used in the geopolymerization process [13,21]. There is a solid or liquid form of an alkali activator. Generally, cement combined with activator and precursor is favored and water is used as a mixture. To produce an alkaline activator in order to balance the negative electrode of alumina with silica, concentrated alkaline aqueous hydroxide solutions or silicate solution which is usually containing potassium (K) or soluble alkali metal sodium (Na) base are used [22]. Most researchers conclude that the optimum ratio of Na_2SiO_3/NaOH is equal to 0.8-1.0 [23, 24]. Meanwhile, the optimum ratio of metakaolin to alkali activator is equal to 0.8 with 10 M of NaOH solution [23].

Fibers. Reinforcement of concrete with the inclusion of fibers is generally used to increase the mechanical properties of metakaolin geopolymer especially in terms of flexural strength and toughness. Fibers and synthetic particles in reinforcement of metakaolin geopolymer such as steel [24-28], polypropylene [29], aluminum [30], carbon nanotubes [20], polyacetal [31], slag [32], and polyvinyl alcohol (PVA) [33] have been studied. On the same time, natural fibers such as jute [34], palm oil [35], corn husk [36], wool [37], rice husk [38], bamboo [39-41], basalt [42-46,48] malva [47], and fique [48] have been investigated as well.

Hooked steel fiber is widely used for OPC concrete reinforcement. The material properties of fibers are usually more dominant in affecting the performance of a reinforced geopolymer composite than binders [5]. The role of the fiber is very important as it is mainly reflected when the concrete starts to crack and it also improves the post- cracking performance as there is the fiber bridging of the crack section. It is said that adding steel fibers to concrete can produce a better crack control effect and improve the tensile strength before and after cracking initiates [25]. The inclusion of steel fibers could help to improve fatigue strength and dynamic resistance of the concrete. However, as the amount of steel fiber added increases, the workability of concrete will decrease [25].

3. Mechanical Properties of Geopolymer Concrete

Compressive Strength. Fiber content were set to 0.25%, 0.50%, 0.75%, 1%, 1.5% and 2% by volume that has been conducted by previous study [22]. The concrete mixture was made in cubes of size 150 mm × 150 mm × 150 mm to measure the compressive strength. The test will be carried out in 3 days, 7 days, and 28 days before crushing. The results of the test for 3 days, 7 days, and 28 days curing with different percentages of the addition of hooked steel fibers were summarized as in Figure 2. The results depicted that there is a significant strength improvement in the mixture of steel fiber reinforced concrete. The optimum fiber content of the compressive strength of the cube was found to be 1% [49].

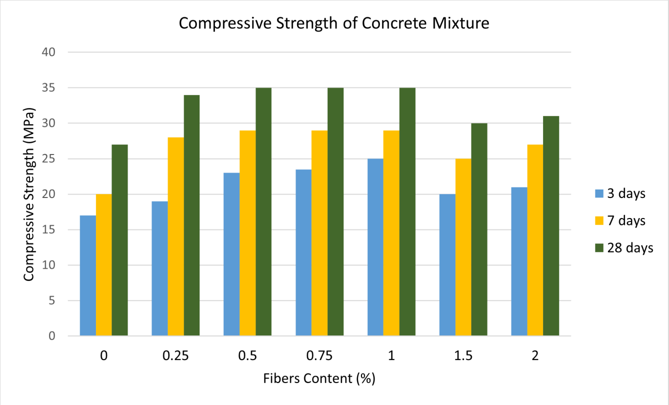

Fig. 2. Compressive strength versus fibers content [49]

In the other study, Malik et al. stated the improvement of compressive strength by the addition of fibers is equal to 31.79% compared to unreinforced geopolymer concrete [50] where unreinforced concrete shows a compressive strength equal to 34 MPa. The reason for improvement to the compressive strength is due to the synergistic and bridging effect in the matrixes in which the propagation of cracks was stopped by the fibers. A previous study on the metakaolin geopolymer concrete found a method to produce high compressive strength of unreinforced metakaolin geopolymer concrete which is by addition of slag where 80 MPa was obtained [51]. The reinforcement of metakaolin-based geopolymer concrete with the addition of another type of fibers such as polyacrylonitrile (PAN) fibers increases the compressive strength to 99.84 MPa at fibers addition equal to 0.8% by volume [52].

Some studies claimed the maximum improvement of compressive strength for metakaolin geopolymer concrete with reinforcement of fibers is about 65% compared to unreinforced metakaolin geopolymer concrete [53]. Metakaolin-based geopolymer concrete used in this study is 50% of metakaolin and 50% of fly ash. However, previous studies have also reported that there is no significant impact of steel fiber addition on the compressive strength of concrete [54]. In fact, there is a study that shows a slight reduction in the compressive strength of metakaolin geopolymer concrete. This is found by Borges et al. where PVA fibers with a dimension of 8 mm of length and 40 μm of diameter were used at a proportion of 1% and 2% (by volume) cured for 28 days [55]. The results showed a reduction in compressive strength in which the unreinforced metakaolin geopolymer matrix obtained 61 MPa while the reinforcement samples of 1% and 2% of fibers addition produced 59 MPa and 50 MPa respectively. However, this reduction in compressive strength does not automatically decrease the value of flexural strength where the flexural strength of this sample at 2% is 8 MPa compared to the unreinforced matrix which is equal to 4 MPa [55]. Ekaputri et al. also observed similar results where the addition of PVA fibers at 0.3% and 0.6% reduced the compressive strength of metakaolin geopolymer concrete compared to the unreinforced matrix material [56]. Both researchers which are Borges et al. and Ekaputri et al stated the reduction of compressive strength value with the addition of fibers is related to the number of voids that present from the geopolymer samples [55,56].

Besides, curing temperature is one of the factors that reflect the compressive strength of geopolymer concrete. This is due to the compressive strength that is related to the geopolymer process There is a study about the effect of curing temperature on the geopolymer process as summarized in Table 2 [52]. The geopolymerization process undergoes two steps. First, the geopolymer was dried at 40°C for 2 hours. It is to overcome the loss of water which can cause geopolymer cracking. Second, the geopolymer was heating up at a higher degree for 24 hours to determine the excellent mechanical properties of geopolymer. The result showed that the total heat evolved at 60°C has achieved 1796 J/g. It is the highest total heat evolved. This is proven that the geopolymerization process is favorable. It has achieved the highest compressive strength at 60°C. Thus, the optimum curing temperature for geopolymerization process is 60°C.

TABLE 2

The effect of curing temperature on compressive strength for 24 hours [52]

Step 1	Step 2	Total Heat Evolution (Jg^{-1})	Compressive Strength (MPa)
40°C for 2 hours	30°C	497.07	7.03
40°C for 2 hours	40°C	1267.76	8.55
40°C for 2 hours	50°C	1414.58	11.77
40°C for 2 hours	60°C	1796.50	17.87
40°C for 2 hours	70°C	1480.82	13.77
40°C for 2 hours	80°C	1149.59	13.13

Flexural Strength. Flexural strength of 7 days and 28 days of the fiber-reinforced geopolymer concrete and the control specimen has been discussed from the previous study as summarized in Figure 3 [23]. Based on the result, the control specimen of 7 days and 28 days flexural strengths were found 5.82 MPa and 7.11 MPa, respectively. By adding 0.15%, 0.20%, and 0.25% by volume of hybrid fibers into the mixture of geopolymer concrete at 28 days, the flexural strength generates approximately 56%, 33%, and 51% improvement. The addition of 0.15% fibers shows the maximum flexural strength of the optimal hybrid fiber content. By comparison, the short fibers are greater against smaller cracks while the long fiber is activated at higher loading conditions to prevent major cracks [30].

Besides, a report studies the flexural strength test in a different type of concrete [25]. The result indicated that the addition of steel fiber in geopolymer concrete causes greater flexural strength. This is supported by other researchers where they have claimed that the addition of steel fibers which is below 2% will increase the flexural strength of metakaolin geopolymer concrete cured at ambient temperature [53]. It has greater flexural strength than a normal geopolymer concrete. This is because of the mechanical development which is contributed by the high modulus of elasticity of the steel fiber in geopolymer concrete. The steel fibers addition in geopolymer concrete influences flexural strength at the low fiber content which is around 0.75% of fibers addition [57]. The improvement of flexural strength for geopolymer concrete with the addition of steel fibers seems significant compared to compressive strength.

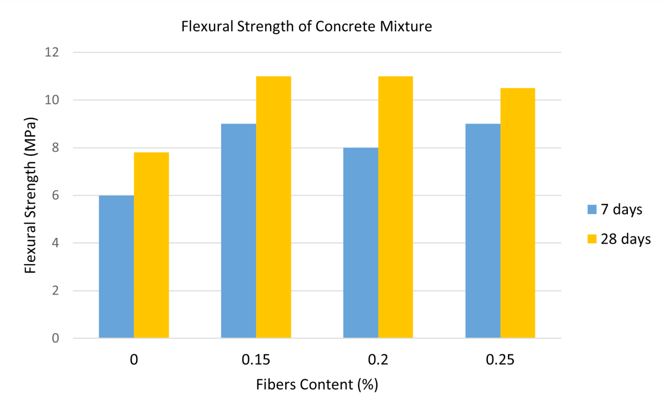

Fig. 3. The flexural strength of fiber reinforced geopolymer concrete [30]

There is another study on metakaolin geopolymer matrix with the addition of class F fly ash where steel fibers were added for reinforcement [27,28]. The unreinforced metakaolin geopolymer composites that were produced showed a comparable value in flexural strength compared to the conventional OPC concrete. The study was conducted with 2% of steel fibers addition and the results showed an increase to the flexural strength value which is higher than the addition of 2% of PVA [27,28].

There is another type of reinforcement in a composites geopolymer called hybrid reinforcement in which two different types of fibers were added into the matrices. This kind of reinforcement normally consisted of 2 different materials that represent different properties were added to gain the synergy effect [58]. Previously, steel fibers incorporated with plastic fibers are most often used in geopolymer reinforcement that involved hybrid reinforcement. An example of this hybrid reinforcement is between short steel and PP fibers [59-61]. However, most of the hybrid reinforcement is found to be applied on fly ash-based geopolymer concrete instead of metakaolin-based geopolymer concrete. There is a limited study involved of metakaolin-based geopolymer composites with reinforcement of hybrid fibers which is between short steel and PVA fibers [27,28]. The experiment was conducted with the inclusion of 1% of steel fibers incorporated with 1% of PVA fibers and the metakaolin geopolymer matrix was blended with class F fly ash and testing was performed at 28 days [27,28]. The results show a sample of metakaolin-based geopolymer composite with hybrid reinforcement exhibit higher flexural strength compared to the sample with reinforcement of only 2% PVA fibers [27,28]. However, this hybrid reinforcement shows lower flexural strength compared to the reinforcement of composites with only 2% of steel fibers addition [27,28].

The previous study also found an improvement from 4 MPa to 13.76 MPa for flexural strength obtained by reinforcement of metakaolin geopolymer concrete with 0.8% of PAN fibers addition [61]. The flexural enhancement towards metakaolin geopolymer concrete was significant. Meanwhile, Celik et al. found the optimum of polyamide (PA) fibers added to the geopolymer matrix composed of metakaolin, slag, and colemanite waste is at 1.2% that produced 11.4 MPa compared to unreinforced matrix material of 8.8 MPa cured at 28 days [58]. However, there is almost no improvement to the compressive strength for this sample [58]. The reinforcement of metakaolin based geopolymer concrete with PA shows a lower mechanical improvement compared to basalt and PVA fibers but they obtained better performance than composites with polyolefin fibers.

Fiber reinforced geopolymer composites also made from mixing of metakaolin and fly ash Class F that has been done in Hong Kong in which PVA fibers have been used (length: 6 mm and diameter: 14 μm) [63]. In this study, 1% and 2% by volume of fibers were added into the matrices. Research of metakaolin-based geopolymers also involved fly ash Class C [64]. Geopolymer composites investigated by Zhang et al. [65] consist of metakaolin and fly ash produced 6.5 MPa of flexural strength. The flexural performance of this sample increase with PVA fibers addition from 0% to 1.2% by volume. The best fiber addition is at 1.2% which 10 MPa of flexural strength was obtained [65]. There is another research involved of metakaolin geopolymer matrix with addition of fly ash Class F where two dimensions of PVA fibers were used which are the length of 8 mm with a diameter of 40 μm [27,28] and length of 12 mm with a diameter of 0.1 mm [68]. Fibers addition for both types is equal to 2% and testing was performed at 28 days. Results showed flexural strength for both types of samples obtained lower and comparable value compared to conventional OPC concrete. However, these geopolymer composites were found to be more ductile in the cracking mechanism [27, 28]. Based on the previous data, higher flexural strength can be achieved by the addition of a smaller dimension of fibers which is smaller in length and diameter. Besides, there is another research conducted related to geopolymer composites made from metakaolin and slags with reinforcement of PVA fibers (length: 7 mm and diameter: 18 μm) [68]. Results show unreinforced metakaolin geopolymer composites produce flexural strength of 6.9 MPa and reinforcement of metakaolin geopolymer composites at 1.0% of PVA fibers increases the value up to 11.2 MPa [68]. Metakaolin-based geopolymer matrices contain slag and colemanite waste from Turkey obtained 8.8 MPa of flexural strength and improved to 12.2 MPa with the addition of 1.2% of PVA fiber (length: 8 mm and diameter: 39 μm) [58]. The metakaolin geopolymer composites with reinforcement of PVA show the second-highest effect to the improvement of flexural (after basalt fibers) with the best improvement of compressive strength compared to others [58].

Polypropylene (PP) also was previously added into both fly ash and metakaolin-based geopolymer [67,68]. However, at the first stage, the results of mechanical performance do not show positive effects at a low fibers content which is lower than 1.0% [69,70]. Further studies involved PP reinforcement in metakaolin geopolymer shows an improvement to the mechanical performance at low fibers addition. The metakaolin was produced by calcination of kaolin at 900°C for 6 hours with the addition of short PP fibers (length of 3 mm and diameter of 10 μm) [71]. Fibers below 0.75% by weight were added and the sample was tested on the 3rd day. Results show an increase in compressive and flexural strength depending on the addition of the fibers. The optimum of fibers addition for compressive strength is at 0.5% that produces 52.3 MPa. Meanwhile, the highest flexural strength recorded was 9.4 MPa at 0.75% of fibers addition. The compressive and flexural strength of unreinforced metakaolin geopolymers on the 3rd day was 41.5 MPa and 5.5 MPa respectively [69]. Further research also has been done where Chen et al. enhance the mechanical performance by the addition of polycyclic emulsion (PAA) into the metakaolin geopolymer matrix [72]. The PP used in the investigation was changed to 8 mm long and a diameter of 40 μm which is longer and bigger than the previous fibers. Results show the flexural strength without the addition of fibers was enhanced to 7 MPa which is higher than the previous metakaolin geopolymer. Meanwhile, the addition of 0.2% of PP fibers increases the flexural strength of modified metakaolin geopolymers to 9.2 MPa [72].

Besides, there is research that uses polyvinyl chloride (PVC) fibers as reinforcement in metakaolin-based geopolymer concrete [68]. Slag was added to the metakaolin matrix and tested was conducted with the addition of 1% of PVC addition with a length of 7 mm and diameter of 400 μm. Unreinforced metakaolin composites obtained 6.9 MPa, meanwhile, the reinforced metakaolin composites increase the flexural strength up to 10 MPa [68]. This result shows the flexural strength of this sample is slightly lower compared to composites with reinforcement of PVA.

3. Summary

The review on the mechanical properties of metakaolin-based geopolymer concrete has been discussed including the introduction, raw materials, compressive, and flexural strength. It can be summarized that metakaolin geopolymer concrete has a high potential to replace OPC concrete to reduce the emission of CO_2. The mechanical properties of reinforced metakaolin geopolymer concrete also shown an excellent performance. The compressive strength of geopolymer concrete can be improved with the addition of steel fibers up to 65%. Besides a normal metakaolin geopolymer concrete, there is a researcher conducted research on a mixture of metakaolin with slag and composite metakaolin geopolymer which is 50% metakaolin mixed with 50% fly ash that resulting in the improvement of compressive strength. Besides, there have some studies from previous experiments that show almost no significant effect on the addition of fibers. There also study stated a slight reduction in compressive strength with the addition of fibers that have been mentioned in this review. Besides, the flexural strength of geopolymer concrete is increased with fiber addition until a maximum at around 0.75% of fiber addition. Aging time shows improvement to the flexural strength. Addition of various percentages of fibers shown an improvement to the flexural strength. There is an improvement of flexural that involved hybrid metakaolin geopolymer (metakaolin mixed with class F fly ash, metakaolin mixed with slag & metakaolin mixed with slag and colemanite) also stated in this review. Comparison of different types of fibers to the flexural strength also has been mentioned. The contribution of hybrid reinforcement also has been discussed previously by researchers and shows an effect on the flexural. Various types of fibers and dimensions of fibers as reinforcement in metakaolin geopolymer concrete have been compared as well. Overall, the researches that have been done related to the metakaolin geopolymer is limited compared to fly ash geopolymer. This is due to the performance of metakaolin geopolymer is lower. This is the reason most researchers developed metakaolin-based geopolymer by mix with other types of the precursor such as slag, fly ash, and colemanite to increase the mechanical performance.

Acknowledgments

This research was funded and supported by the Centre of Excellent Geopolymer & Green Technology (CEGeoGTech) and University Malaysia Perlis (UniMAP), Malaysia.

REFERENCES

[1] H.M. Jonkers, A. Thijssen, G. Muyzer, O. Copuroglu, E. Schlangen, Ecol. Eng. **36** (2), 230-235 (2010).

[2] L. Wu, Z. Lu, C. Zhuang, Y. Chen, R. Hu, Mater. **12**, 3773 (2019).

[3] K.H. Mo, U.J. Alengaram, M.Z. Jumaat, Mater. **120**, 251-264 (2016).

[4] W.T. Chan, Civ. Eng.Dimens.**173** (17), 126-132 (2015).

[5] N. Ranjbar, M. Zhang, Cem. Concr. Compos. **107**, 103498 (2020).

[6] W.W.A. Zailani, M.M.A.B. Abdullah, M.F. Arshad, R.A. Razak, M.F.M. Tahir, R.R.M.A. Zainol, M. Nabialek, A.V. Sandu, J.J. Wysłocki, K. Błoch, Materials **14**, 56 (2021).

[7] C.K. Ma, A.Z. Awang, W. Omar, Constr. and Build. Mater. **186**, 90-102 (2018).

[8] https://www-scopus-com.ezproxy.unimap.edu.my/term/analyzer.url

[9] Y.M. Ghugal, V.D. Sabale, S.S. More, Asian J. of Civ. Eng. **18** (7), 1113-1124 (2017).

[10] S. Abdallah, M. Fan, X. Zhou, S. Le Geyt, Int. J. Concr. Struct. Mater. **10** (3), 325-335 (2016).

[11] Z. Tao, Z. Pan, Ned U. J. of Res. **2**, 113-128 (2019).

[12] S. Riahi, A. Nemati, A.R. Khodabandeh, S. Baghshahi, Mater. Chem. Phys. **240**, 122223 (2020).

[13] A.B. Moradikhou, A. Esparham, M. JamshidiAvanaki, Int. J. Concr. Struct. Mater. **251**, 118965 (2020).

[14] Z. Yunsheng, S. Wei, L. Zongjin, Appl. Clay Sci. **47**, 271-275 (2010).

[15] B.B.D. Kenne, A. Elimbi, M. Cyr, J.M. Dika, H.K. Tchakoute, J. Asian Ceram. Soc. **3**, 130-138 (2015).

[16] P. Rovnan´ık, Constr. Build. Mater. **24**, 1176-1183 (2010).

[17] M.R. Rowles, B.H.O'Connor, J. Am. Ceram. Soc. **92** (10), 2354-2361 (2009).

[18] H. Zhu, Z. Zhang, F. Deng, Y. Cao, Constr. Build. Mater. **48**, 124-130 (2013).

[19] H.Y. Zhang, V, Kodur, B. Wu, L. Cao, S.L. Qi, J. Mater. Civ. Eng. **28** (2), 1-12 (2016).

[20] W. Zhao, Y. Wang, X. Wang, D. Wu, Ceram. Int. **42**, 6329-6341 (2016).

[21] O.H. Li, L. Yun-Ming, H. Cheng-Yong, R. Bayuaji, M.M.A.B. Abdullah, F.K. Loong, T.A. Jin, N.H. Teng, M. Nabiałek, B. Jeż, N.Y. Sing, Magnetochemistry **7** (1), 9 (2021).

[22] Y.H.M. Amran, R. Alyousef, H. Alabduljabbar, M. El-Zeadani, J. Clean. Prod. **251**, (2020).

[23] N.A. Jaya, Y.M. Liew, C.Y. Heah, M.M.A.B. Abdullah, AIP Conf. Proc. **2045**, 020099 (2018).

[24] T. Luukkonen, Z. Abdollahnejad, J. Yliniemi, P. Kinnunen, M. Illikainen, Cem. Concr. Res. **103**, 21-34 (2018).

[25] M. A. Faris et al., Mater. Sci. For. **857**, 388-394 (2016).

[26] W.M. Kriven, J. Bell, M.Gordon, Ceram. Eng. Sci. Proc. **25** (1), 57-79, (2004).

[27] F.U.A. Shaikh, Mater. Des. **50**, 674-682 (2013).

[28] F.U.A. Shaikh, Constr. Build. Mater. **43**, 37-49 (2013).

[29] W.D.A. Rickard, L. Vickers, A.van Riessen, Appl. Clay Sci. **73**, 71-77 (2013).

[30] A.B. Moradikhou, A. Esparham, M.J. Avanaki, J. Civil Eng. Mater. App. **3** (4), 193-201(2019).

[31] W. Zhao, Y. Wang, X. Wang, D. Wu, Ceram. Int. **42**, 6329-6341 (2016).

[32] E. Rill, D.R. Lowry, W.M. Kriven, Cer. Eng. Sci. Proc. **31** (10), 57-69 (2010).

[33] C. Leiva, L.F. Vilches, J. Vale, C. Fernández-Pereira, Fuel **84**, 1433-1439 (2005).

[34] K. Sankar, W.M. Kriven, Cer. Eng. Sci. Proc. **38** (10), 39-60 (2015).

[35] S.M.A. Kabir, U.J. Alengaram, M.Z. Jumaat, A. Sharmin, A. Islam, Adv. Mater. Sci. Eng. **2015**, 1-15 (2015).

[36] S.S. Musil, P.F. Keane, W.M. Kriven, Cer. Eng. Sci. Proc. **34** (10), 123-133 (2014).

[37] M. Alzeer, K.J.D. MacKenzie, J. Mater. Sci. **47**, 6958-6965 (2012),

[38] U.H. Heo, K. Sankar, W.M. Kriven, S.S. Musil, Cer. Eng. Sci. Proc. **38** (10), 87-102 (2015).

[39] K. Sankar, R.A. S´a Ribeiro, M.G. S´a Ribeiro, W.M.Kriven, J. Am. Ceram. Soc. **100**, 49-55 (2017).

[40] R.A.S´a Ribeiro, M.G. S´a Ribeiro, K.Sankar, W.M. Kriven, Constr. Build. Mater. **123**, 501-507 (2016).

[41] R.A. S´a Ribeiro, M.G. S´a Ribeiro, K. Sankar, G.P. Kutyla, W.M. Kriven, Ceram. Eng. Sci. Proc. **37** (7), 123-133 (2017).

[42] W.M. Kriven, J.L. Bell, M. Gordon, Ceram. Trans. Ch **15**, 227-250 (2003).

[43] W.M. Kriven, J. Bell, M. Gordon, Ceram. Eng. Sci. Proc. **25**, 5, 57-79 (2004),

[44] S. Musil, Dissertation, University of Illinois at Urbana-Champaign, Urbana, IL, USA (2014).

[45] D. Ribero, W.M. Kriven, J. Am. Ceram. Soc. **99** (4), 1192-1199 (2016).

[46] S.S. Musil, G. Kutyla, W.M. Kriven, Eng. Sci. Proc. **33**, (10), 31-42 (2013).

[47] K. Sankar, W.M. Kriven, Green composite: sodium geopolymer reinforced with malva fibers, J. Am. Ceram. Soc., (in preparation), (2017).

[48] K. Sankar, W.M. Kriven, Cer. Eng. Sci. Proc. **38** (10), 61-78 (2015).

[49] A. Abolmaali, A. Mikhaylova, A. Wilson, J. Lundy, Transp. Res. Rec. **2313** (1), 168-177 (2012).

[50] M.A. Malik, M. Sarkar, S. Xu, Q. Li, Appl. Sci. **9**, 1953 (2019).

[51] O.A. Abdulkareem, A.M. Mustafa Al Bakri, H. Kamarudin, I. Khairul Nizar, A.E.A. Saif, Constr. Build. Mater. **50**, 377-387 (2014).

[52] M.S. Muñiz-Villarreal et al., Mater. Lett. **65**, 995-998 (2011).

[53] S.P. Priyadharshini, A.R.R. Kalaiyarrasi, Int. J. Recent. Sci. Res. **9** (8), 28303-28305 (2018).

[54] V. Afroughsabet, L. Biolzi, T. Ozbakkaloglu, R. Hu, Compos. Struct. **181**, 273-284 (2017).

[55] P.H.R. Borges, A. Bhutta, L.T. Bavuzo, N. Mater. Struct. **50**, 148-160 (2017).

[56] J.J. Ekaputri, S. Junaedi, Procedia Eng. **171**, 572-583 (2017).

[57] S. Iqbal, I. Ali, S. Room, S.A. Khan, A. Ali, Mater. Struct. Constr. **52** (3), 1-10(2019).

[58] A. Celik,; K. Yilmaz, O. Canpolat, M.M. Al-Mashhadani, Y. Aygörmez, M. Uysal, Constr. Build. Mater. **187**, 1190-1203 (2018).

[59] P. Sukontasukkul, P. Pongsopha, P. Chindaprasirt, S. Songpiriyakij, Constr. Build. Mater. **161**, 37-44 (2018).

[60] N.P. Asrani, G. Murali, K. Parthiban, K. Surya, A. Prakash, K. Rathika, U. A. Chandru, Constr. Build. Mater. **203**, 56-68 (2019).

[61] J.R.A. Goncalves, Y. Boluk, V. Bindiganavile, Mater. Struct. **51**, 42 (2018).

[62] C. Luo, A.C. Wang, Key Eng. Mat. **697**, 608-611 (2015).

[63] Y. Zhang, W. Sun, Z. Li, J. Mater. Sci. **41**, 2787-2794 (2006).

[64] S. Peijiang, W. Hwai-Chung, Cem. Concr. Compos. **30**, 29-36 (2008).

[65] P. Zhang, K. Wang, J. Wang, J. Guo, S. Hua, Y. Ling, Ceram. Int. **46**, 20027-20037 (2020).

[66] F.U.A. Shaikh, Mater. Des. **50**, 674-682 (2013).

[67] F.U.A. Shaikh, Constr. Build. Mater. **43**, 37-49 (2013).

[68] A. Natali, S. Manzi, M.C. Bignozzi, Procedia Eng. **21**, 1124-1131 (2011).

[69] F. Puertas, T. Amat, A. Fernandez-Jimenez, T. Vazquez, Cem. Concr. Res. **33**, 2031-2036 (2003).

[70] F. Puertas, T. Amat, T. Vázquez, Mater. Constr. **259**, 69-84 (2000).

[71] Z. Zhang, X. Yao, H. Zhu, S. Hua, Y. Chen, J. Cent. South Univ. Technol. **16**, 49-52 (2009).

[72] X. Chen, Z. Zhou, W. Shen, G. Zhu, X. Ge, Constr. Build. Mater. **190**, 680-690 (2018).