https://doi.org/10.1051/e3sconf/202344501007

# Properties of ultra-high-performance mortar containing eco-friendly wollastonite microfibers for green and sustainable infrastructure

*Steve W.M* Supit [1*], and *Tomoya* Nishiwaki [2]

[1]Civil Engineering Department, Manado State Polytechnic, Jl. Raya Politeknik Kel. Buha, Manado, Indonesia
[2]Graduated School Engineering, Tohoku University, Aoba-6-3 Aramaki Aoba Ward, Sendai, Japan

**Abstract.** Wollastonite has become one of the potential pozzolanic micro-fibers material that can be used to improve the characteristics of cement-matrix composites. This study was conducted with the aim to investigate experimentally the properties of high-strength mortar containing wollastonite as an additive material with percentage of 1.2, 2.4, 4.8, and 9.6% by weight of binders. Water and sand to binder ratio of 0.2 and 2.5, respectively, were used to form high-strength mortar specimens for mechanical properties testing including compressive strength and three-point loading on flexural strength test. Microstructural analysis was also conducted to assess the reinforcing effects and hydration products that might be affected due to the inclusion of wollastonite micro-fibers. The results show that mortar with 1.2-4.8% of wollastonite content reached 12% higher resistance on compression load with respect to the control mortar. More significant improvement can be observed in flexural strength results whereas the wollastonite showed its reinforcing capability in bridging the micro-cracks resulted in more ductile and toughness matrix in carrying the high load carrying capacity. Moreover, wollastonite also has a capability to pore refinement as evident from the sorptivity results. Furthermore, wollastonite micro-fibers can be an alternate source material for durability improver that leads to sustainable infrastructure.

## 1 Introduction

Infrastructure development has been rising rapidly and is expected to consume an increasing amount of energy due to the increases in both population and the economy. Cutting the energy expenditure of buildings has become the main target to meet the sustainability criteria, as well as the reduction of $CO_2$ emissions that influences the stabilization of climate change. On the area of construction materials, the use of waste and/or recycled materials is now being undertaken to address the environmental impacts of using cement and natural aggregates. As reported, during 0.9 ton of cement manufacturing, on average 1 ton of carbon dioxide can be released into the atmosphere, [1] making cement production responsible for nearly 8-10% of

---

* Corresponding author: steve.supit@sipil.polimdo.ac.id

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

global $CO_2$ emissions. [2] Moreover, there is an adverse environmental impact due to rock mining, as well as the reduction of natural resources. Urgent action is required to reduce this rate of consumption through innovation and the technological modernization of green concrete production.

Green concrete can be defined as concrete that uses waste or recycled materials to achieve a high degree of performance without environmental destruction during its production. The use of green concrete is expected to minimize greenhouse gas emissions and provide more economic benefits in terms of the energy and maintenance costs, leading to sustainable construction materials. Some innovative methods have been researched such as the use of waste materials from industry (fly ash, silica fume, blast furnace slag) [3], agriculture (rice husk ash, corncob ash, sawdust ash, palm oil fuel ash) [4], and municipality functions (glass and plastics) [5,6] to reduce the level of cement consumption or natural aggregates when making concrete. Other innovations are related to architecture and smart structural design, reducing the dimensions of structural elements such as columns, walls, the foundation, and beams without compromising structural safety [7]. This innovation drives the extensive research on ultra-high-performance concrete and ultra-high-performance fiber-reinforced concrete for the utilization of lightweight and slender structures with some characteristics such as high strength on compression (150MPa to 200MPa), high tensile strength (8MPa <), high rheology properties and greater durability properties due to the higher packing density. However, since the production cost can be more expensive than that of conventional mixtures, its potential applications are still limited to repairing purposes, bridges with a long-span dimension and in some critical infrastructures like the military and nuclear plant buildings [8]. Proposing new methods and new materials is required to decrease the final cost of ultra-high-performance concrete and ultra-high-performance fiber-reinforced concrete.

Recently, there has been progress in the field of fiber reinforcement systems, specifically cement-based composite mixtures. The variation of the fibers has been reported to effectively contribute to the performance of the concrete. For example, steel fibers, poly-propylene fiber, basalt fiber, and carbon fiber have all been used [9]. Most research has claimed the ability of fibers to improve the ductility of the concrete components, hence the limited crack development under tensile and flexural loads.

One of the fibers that is most discussed recently is wollastonite micro-fibers with needle-like and fibrous crystal forms. It is normally used in the ceramic, paper, and metallurgy industries [10]. Wollastonite is known as a metasilicate material with high CaO around 48% and $SiO_2$ at 52%, giving it the potential to be incorporated into a cement-based mixture. Naturally, wollastonite is available to be used in aspect ratios of 3:1 to 20:1 [11], and it can be modified through synthetic production. In terms of its availability, some countries such as China, India, Japan, South Korea, the United States, Mexico and other European countries like Spain, Italy, and Sweden have been reported to use wollastonite deposit with a variety of quality based on the geological formations observed. Environmentally, wollastonite is a non-carbonate material, thus its presence to replace limestone in cement manufacturing can be expected, where 1% wollastonite as a replacement for limestone reduced the thermal energy by approximately 4 kcal/kg clinker and 0.013 t $CO_2$/t clinker [12].

Some experimental studies have been conducted to evaluate the behavior of cement-based composite matrices containing wollastonite. Reference [13] reported the effects of using ground wollastonite based on the conduction of strength and cement hydration tests. Other studies also reported in 2021 using a numerical simulation conducted by [14] evaluated the influence of wollastonite when binding calcium hydroxide. The results showed that the addition of wollastonite led to the reduction of the specified volume because of the CH binding phase. The internal stress of the material was also reduced, which increased the compression and bending hardening, especially when using the optimum composition of 0.25% wollastonite. Similar studies have also been reported by (15-17).

This research aims to evaluate the properties of wollastonite in ultra-high-performance mortar (UHPM) based on its compressive and flexural strength properties, water absorption and corrosion resistance test results. Understanding this area is important since research on the use of wollastonite as an additive material to improve the toughness and durability properties of ultra-high-performance mortar and concrete with a strength of more than 100MPa is still in a very limited stage, particularly when using a very small percentage mixed with silica fume cement. Some debates still exist on the hydration products that might be formed when wollastonite is included in the cement-based matrix. From this experiment, the most influential parameters of wollastonite can be discovered to support the implementation of green and sustainability construction.

## 2 Methods

A type of cement containing 10% silica fume (binder), silica sand No.6 and wollastonite sourced from NYCO Minerals, Inc., were used in this experiment. Based on the material property data, the wollastonite used in this experiment had a particle size of around 2-22μm, a specific surface area of $1.8m^2g$, and contained 46.36% CaO and 51.6% $SiO_2$ with other elements like $Al_2O_3$, $Fe_2O_3$, $K_2O$, MgO, MnO, and $TiO_2$. Wollastonite microfibers were incorporated into the cement binders to form a very high-strength mortar with a target compressive strength higher than 150 MPa. In this experiment, wollastonite was used as an additive material at a variation of percentages, i.e., 1.2%, 2.4%, 4.8%, and 9.6%, by wt. of binder, mixed at a ratio water/binder = 0.2 and sand/binder = 0.35. In this mixture, a superplasticizer and defoaming agent were also used to maintain consistency and increase the density of the specimens.

In this study, the mortar specimens were designed to evaluate their properties based on compressive and flexural strength, water absorption and accelerated corrosion resistance tests. The testing procedure was conducted based on JIS A 1108 for the compressive strength test, while the flexural strength and water absorption tests were carried out according to JCI-S-002-2003 and ASTM C1403 standard. The samples were tested after letting them sit at room temperature for 48 hours followed by temperature curing at 90ºC for 48. The samples were then stored at room temperature until the 7th day of testing. The accelerated corrosion test was conducted by recording the variation of current with time through the impressed anodic potential between the sample of rebar and steel plate. In this test, deformed steel bars that were 10mm diameter and 100mm in length were inserted at the centre of 100mmx50mm cylinder specimens. The reinforced mortar specimens were immersed in a 5% sodium chloride solution and the current reading was recorded using the automatic corrosion detector until the initiation of corrosion was detected. For the microstructure analysis, X-Ray Diffraction was conducted to support the findings.

## 3 Result and Discussion

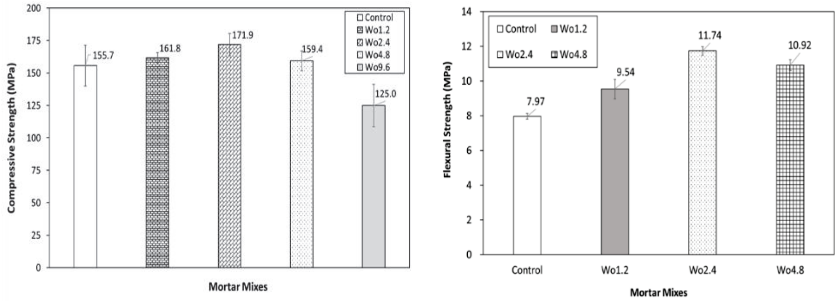
### 3.1 Compressive Strength of the UHPM Reinforced with Wollastonite

The compressive strength values of the mortar with very high strength performance are presented in Figure 1a. The control specimen and wollastonite specimens with variation percentages of 1.2%, 2.4%, 4.8%, and 9.6% by wt. were considered in this figure to discuss the potential effects of adding wollastonite regarding improving the strength of the sample containing cement only. Based on the results here, the compressive strength of the wollastonite samples was observed to be higher than the reference sample, especially when the dosage is in the range of 1.2% to 4.8%. The highest compressive strength was performed by the mortar sample containing 2.4% wollastonite while making the dosage higher, up to 4.8% and 9.6%, decreased the compression load resistance. Looking at the percentage improvement of the compressive strength of the mortar samples after adding wollastonite, it can be observed that using wollastonite as an additive material with maximum ratio of 4.8% provided strength that was around 3 to 10% higher than the reference mortar. For 9.6% wollastonite, the strength decreased by around 20%. The improvement of strength can be due to the combined properties of the wollastonite providing a reinforcing effect due to its needle-like shape and at the same time, accelerating the pozzolanic reactivity, thus improving the packing density after 7 days of curing [13]. In terms of the percentage of wollastonite used as an additive material, it is noteworthy to mention that the percentage should not be more than 4.8% based on this study.

## 3.2 Flexural Strength of UHPM Reinforced with Wollastonite

The effects of the wollastonite to do with the flexural strength of the mortar with a very high strength are discussed in this session. As expected, the effectiveness of the wollastonite can be observed to be more pronounced in flexural strength behaviour than compressive strength. Figure 1b presents the change in the flexural strength values when adding wollastonite to the mortar mixtures. It can be clearly observed that there is a significant improvement in bending load resistance when the mortar was reinforced with 1.2%, 2.4%, and 4.8% wollastonite. There is a similar trend as in the compressive strength results, where the mortar with a 2.4% addition of wollastonite reached the highest strength with a flexural load at 11.74 MPa, which is 32% higher than control mortar. The use of a small amount of 1.2% wollastonite also showed a 16% increase in flexural strength but this decreased when the level of replacement was 4.8% by wt. These results confirm the more significant improvement in flexural strength when using a very small percentage of wollastonite as an additive material.

.



(a) (b)

**Fig. 1.** Results of (a) compressive strength and (b) flexural strength

Figure 2 shows the properties of the UHPM with and without wollastonite addition based on stress-displacement curves. It can be clearly seen that the UHPM containing wollastonite performed more actively during the pre-peak area and raised the load until reaching the peak

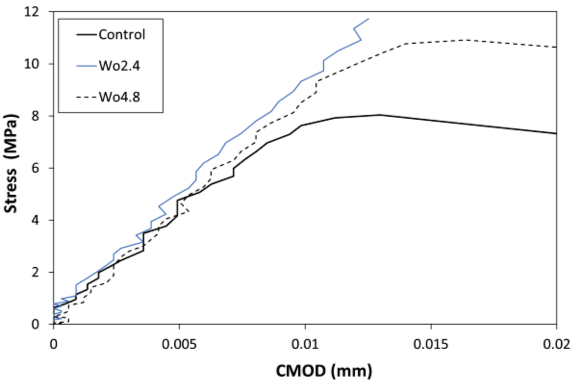


**Fig. 2.** Stress-displacement curves on UHPM with and without wollastonite

Interestingly, even Wo2.4 exhibited the highest resistance for flexural strength and broken fibers after reaching the peak load can be observed. This phenomenon indicates potential brittle behavior due to the higher density of the UHPM incorporated with wollastonite micro-fibers, hindering the typical strain-hardening behaviour of the fiber-reinforcement composite matrix that can be normally remarkable from the long tail formation when the post-peak part is considered. In turn, increasing the amount of wollastonite up to 4.8% resulted in a more pronounced fiber mechanism and higher load carrying capacity when compared to the control UHPM, indicating that a higher fracture energy associated with higher ductility can be achieved by adding a small percentage of wollastonite. The efficiency of the wollastonite in impending crack propagation is reported to be due to its acicular properties that can reduce the width of the crack surface and restrict it from further formation [18]. Wollastonite, when uniformly distributed in the UHPM matrix, could also lead to contributing to the higher bonding of the matrix that imparts a post-cracking load-bearing capacity and improves impact resistance.

When it comes to practicality, the increase in the flexural strength and toughness of the UHPM mortar due to the wollastonite addition could be beneficial to the structural design of large beams and slabs that require a higher amount of reinforcement with high section thickness, since this is mainly governed by its flexural strength. When the presence of tensile performance is not essential to the structural integrity, UHPM containing wollastonite can be used as a fast- setting material for repair and emergent reinforcement to achieve the special requirements needed in the construction field. However, the reinforcement ability of the wollastonite micro-fibers is reported to be dependent on its physical properties, particle size distribution, and volume fraction. It is suggested to use wollastonite microfibers with the same aspect ratio, while a thinner shape that was found more effective at improving the mechanical properties [19].

### 3.3 Water Absorption and Corrosion Resistance of the UHPM Reinforced with Wollastonite

Table 1 presents the properties of the ultra-high-performance mortar for the water absorption tested on the 7th day, referring to the measurement of the absorption rate of the water through capillary suction. The results show that the lowest water absorption rate was found in the UHPM containing 1.2% wollastonite with a water absorption rate of 6 grams/100cm$^2$ and an absorption depth of 0.147 mm (see Table 1). The absorption rate started to increase when adding 2.4 and 4.8% but still performed lower than the control mortar. The effect of wollastonite related to extending the hydration through the reaction with calcium hydroxide, contributing to the CSH formation, can be one of the causes explaining the matrix densification besides the filler effect densifying the structure of the cement matrix and the bridging behaviour [13,20]. Since the increase of the wollastonite content was found to tend to increase the water absorption rate, the proportion of wollastonite addition should be one of the parameters considered to avoid continuous pores in the UHPM matrix. Other factors could be the physical properties of the wollastonite, the water to binder ratio, curing condition, and mixing method.

**Table 1.** Water absorption of the UHPM mortars at 24 hour

| Mix | I (absorption, mm) | $A_T$ - Water absorption (grams/100 cm$^2$) |
|---|---|---|
| Control | 0.193 | 8 |
| Wo 1.2 | 0.147 | 6 |
| Wo 2.4 | 0.165 | 7 |
| Wo 4.8 | 0.174 | 7 |

Figure 3 shows the current-time relationships of both the control and Wo4.8 UHPM specimens where current with time was recorded for 91 days until corrosion cracks appeared on the surface of the specimens. Based on this experiment, it can be clearly seen that the current values of the control mortar are significantly higher than the UHPM containing 4.8% wollastonite. The increase in current for the control mortar was obtained on the 49th day from the beginning of the test with a current value of 3.36 mA under the impressed voltage. In turn, a very low current was detected in the Wo4.8 sample, indicating the slow penetration of chloride ions due to the high density of the mortar with wollastonite addition. After the 49th day, the current of the control mortar sample showed a big jump up to 29.72 on the 77th day and ended at 32.28 on the 91st day. A rapid increase in current flow indicated crack formation on the mortar samples. However, the UHPM mortar sample with wollastonite showed a very high resistance to the penetration of chloride ions with a 100% lower value of current on the 91st day detected compared to the control mortar. These results could be due to the filling properties of wollastonite and the hydration activity that created the improvement of the binding capacity to the steel bar, as well as the enhancement of pore refinement. A similar observation was reported by [21] that the inclusion of combined wollastonite and micro-silica resulted in less porosity and a reduction of the corrosion probability.

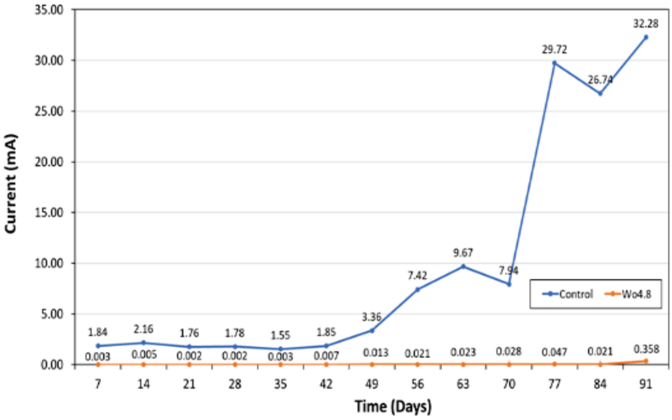


**Fig. 3.** Current-time relationships for the UHPM containing wollastonite

### 3.4 X-Ray Diffraction Analysis of the UHPM Reinforced With Wollastonite

The peak patterns of the UHPM samples containing 2.4% and 4.8% wollastonite as part of the qualitative comparison with the control mortar are shown in Figure 4. It can be identified that there are typical cement hydration products such as calcium silicate ($C_2S$, $C_3S$), calcium hydroxide, and calcium-silicate-hydrate. The presence of wollastonite can be detected in the Wo.2.4 and Wo4.8 samples through the peaks at around 29.98$^{o}$, 26.86$^{o}$ and 23.16$^{o}$ two-theta. The peak pattern of the calcium hydroxide is found to be around 56.5$^{o}$ two-theta, where the UHPM containing wollastonite produced a lower CH intensity compared to the control UHPM. Additionally, the increase in CS volume can be observed in the Wo samples at 41$^{o}$ and 28$^{o}$ two-theta, representing the increased CSH volume.

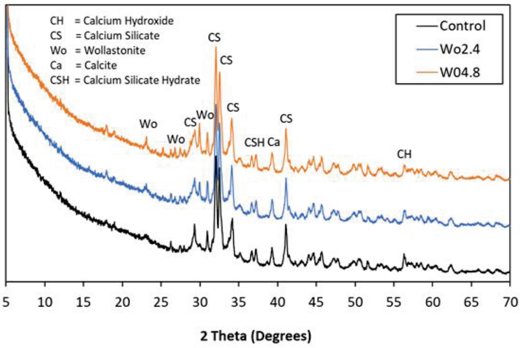


**Fig. 4.** Peak intensity of the UHPM reinforced with wollastonite in the XRD analysis

## 4 Conclusions

The potential development of using wollastonite micro-fibers as an additive in UHPM has been reported in this study with some conclusions are as follow.

- The significant contribution after adding wollastonite to the cement-based composites matrix can be detected in a more pronounced manner due to improving the toughness and ductility of the mortar specimens rather than compression.
- From the XRD analysis, it can be confirmed that the wollastonite addition has contributed to the hydration reaction by reducing the portlandite and increasing the CSH phase.
- In terms of the permeability and corrosion possibility when using wollastonite as an additive in ultra-high-performance mortar, the results confirm that this mixture proportion is essential to produce impermeable and high durable elements that, on exposure to water and chloride ions, can be exploited for repair and rehabilitation when the structures are exposed to marine environment work.
- From the standpoint of sustainability, the ultra-high-performance mortar produced from blended wollastonite and silica fume cement can be an innovative product due to supporting smart structural design that can enhance its service life because of its free cracking properties under both structural and environmental loads. This is at the same time as supporting high early strength and high-speed construction.

The authors acknowledge the Japanese Society for the Promotion of Science, Grant Number JP22F21050, for the support of this study.

# References

1. S. K. Sharma, G. D. R. N. Ransinchung, P. Kumar, and A. K. Roy, International Conference on Advances in Construction Materials and Structures (ACMS-2018) (2018)
2. B. Suhendro, in *Procedia Eng* (Elsevier Ltd, 2014), pp. 305–320
3. B. Han, S. Ding, and X. Yu, Measurement (Lond) **59**, 110 (2015)
4. N. V. S. Kumar and S. V. Satyanarayana, Int J Health Sci (Qassim) 350 (2022)
5. N. Tamanna and R. Tuladhar, The Open Waste Management Journal **13**, 1 (2020)
6. S. W. M. Supit and Priyono, Mater Today Proc **66**, 2990 (2022)
7. A. Al-Hamrani, M. Kucukvar, W. Alnahhal, E. Mahdi, and N. C. Onat, Materials **14**, 1 (2021)
8. H. Abdolpour, P. Niewiadomski, A. Kwiecień, M. Tekieli, and Ł. Sadowski, Constr Build Mater **374**, (2023)
9. G. Jayakumar, M. E. Mathews, T. Kiran, B. S. K. Yadav, B. Kanagaraj, and N. Anand, in *Mater Today Proc* (Elsevier Ltd, 2021), pp. 1148–1153
10. Y. Zhang, H. Zhu, M. Shi, S. Li, and C. Ma, *Effect of Wollastonite Microfiber on the Performance of Engineered Cementitious Composites* (2022)
11. H. E. Yücel and S. Özcan, Constr Build Mater **223**, 165 (2019)
12. S. K. Saxena, M. Kumar, D. S. Chundawat, and N. B. Singh, in *Mater Today Proc* (Elsevier Ltd, 2019), pp. 733–737
13. R. I. Khan and W. Ashraf, Constr Build Mater **218**, 150 (2019)
14. S. S. Dobrosmyslov, A. S. Voronin, Y. V. Fadeev, I. G. Endzhievskaya, and S. V. Khartov, in *J Phys Conf Ser* (IOP Publishing Ltd, 2021)
15. J. Archez, N. Texier-Mandoki, X. Bourbon, J. F. Caron, and S. Rossignol, Constr Build Mater **257**, (2020)
16. A. Jindal, R. N. G. D. Ransinchung, and P. Kumar, International Journal of Transportation Science and Technology **9**, 170 (2020)
17. R. Kumar, Sustainable Construction Materials and Technologies **2016-Augus**, (2016)
18. V. Dey, R. Kachala, A. Bonakdar, and B. Mobasher, Constr Build Mater **82**, 351 (2015)
19. S. Kwon, T. Nishiwaki, H. Choi, and H. Mihashi, Journal of Advanced Concrete Technology **13**, 332 (2015)
20. Z. He, A. Shen, Z. Lyu, Y. Li, H. Wu, and W. Wang, Constr Build Mater **261**, (2020)
21. R. Aghalou Topraghlou, Y. Mohammadi, and M. Jolani Domdomeh, Arab J Sci Eng (2022)