The 2024 World Congress on
Advances in Civil, Environmental, & Materials Research (ACEM24)
19-22, August, 2024, The K hotel, Seoul, Korea

Research on Properties of Eco-Green Ultra-High-Performance Concrete with Distinct Alkali-Activated Contents

*Po-Yuan Su[1) and Wen-Cheng Yeh[2) and Ming-Hui Lee[3)

[1),2),3)] *Department of Civil Engineering,NPUST, No. 1, Xuefu Rd., Neipu Township, Pingtung County 912301, Taiwan*
[1)] *p11233001@mail.npust.edu.tw*

ABSTRACT

The energy-saving and carbon-reducing is an important issue that must be concerned by all world countries for the global climate warming problems. Concrete is one of the most commonly used materials in the world. A lot of cement must be used in concrete production. Based on the concept of environmental protection and resource reuse, the cement less eco-green ultra-high-performance concrete (UHPC) was developed in this study. In the early study stage, the cement will be replaced (50%, 62.5%, 75%, 87.5% and 100%) by the ground granulated blast slag (GGBS) to mix UHPC, and the compressive strength will be tested at 7 and 28-day. Results show that the compressive strength faster decays in the amount of substitution. Therefore, the alkali will be used to activate the activity of GGBS to increase the compressive strength. The distinct contents of alkali and F100 grade GGBS were designed to make cement mortar 50×50×50mm cube specimens. The compressive strength of 14 and 28-day, workability, temperature of alkali liquid and activity index were tested in this study. The experimental results show that the compressive strength of 28-day is only slightly low 0.58% as water-cement ratio (w/c=0.20) and 18.04% as lower w/c=0.25 than ordinary Portland cement (OPC). It shows that the higher strength performance in the case of low w/c ratio and higher alkali activated content; conversely, the lower alkali activated has a slightly effect the strength performance in the trend of higher w/c ratio. Meanwhile, the workability is worse, average between 130-140mm in lower w/c=0.2 ratio; and the workability becomes more worse, average between 120-130mm as the alkali content increases. The activity index is between 74%-99% in w/c=0.20 ratio, between 66%-92% in w/c=0.25. This shows that the GGBS has better property of activity index at lower w/c ratio.

Keywords: UHPC, GGBS, compressive strength, activity index, OPC.

[1)] PhD Student
[2)] Associate Professor
[3)] Professor

1.INTRODUCTION

The research and development of resource recycling industry has always been the goal of countries around the world at present. The resource recycling of industrial by-products has been actively developed for energy conservation, carbon reduction and sustainable management.

Some studies estimate that the world's population will increase reach 8.5 billion by 2030, and 9.7 billion by 2050. Therefore, the development of industries and infrastructure will be accompanied by the quickly growth of population. Meanwhile, the global cement manufacturing produces cement approximately 4.1 million tons and concrete about 10 billion cubic meters every year. Produced 1-kilogram cement will produce 0.1~0.2 kilograms of carbon dioxide and consume 1~2 million joules of energy; for steel manufacturing, it will produce 0.05 kilograms of carbon dioxide and consume 500000 joules of energy (Coffetti 2022).

Concrete is composed of sand, aggregate, cement and water, where, the cement proportion about 10% to 20%, and is considered the second most consumed substance only surpassed by water in the world. Some literatures discussed the issue of carbon dioxide emissions. Between 5 and 7% of the total global anthropogenic CO2 emissions are due to cement production (International Energy Agency and Cement Sustainability Initiative, 2018) (Cadavid-Giraldo 2020).

Global resource extraction has more than double since 1970, with the use of non-metals increasing five times, minerals and fossil fuels increasing by 45%. The non-recyclable use of resources generates a large amount of waste, including municipal solid waste, which is specific to waste generated in urban areas and varies according to the characteristics of different areas (Khajuria 2022), and may Leading to serious environmental consequences such as marine environmental damage and climate change (Khajuria 2022).

Therefore, drop emissions of greenhouse gas by reducing cement production and recycling resources are the urgent to be actively promoted goals.
Rapid economic and social progress around the world due to the natural resource extraction since the industrial revolution. The accelerated the rapid depletion of resources and serious threat to the environment through carbon dioxide emissions because of the large-scale exploitation and use of resources around the world.

An economist Boulding (1996) proposed a circular production system to sustain an economy growing. Recently, the “circular economy” model has been proposed into an ideal solution to approach or even achieve global sustainable economic development. This model addressed the products and materials are designed and managed considering minimization, reuse, recovery, and/or recycling. Despite the promising prospects of the circular economy, it depending highly on the recycled materials within the cycle of production and consumption, with meeting just only 9% of global material needs (Li 2022). Hence, waste reduction and reuse are urgently promoted currently.

The construction of livelihood economy produced industrial by-products for most of every year waste, such as brick, glass, re-steel, fly ash, silica fume and GGBS, etc. Therefore, the scholars around world have actively invested in research and development of green materials. However, it is necessary to find relevant cementitious material that can replace cement reducing the usage amount. In recent years, alkali cementitious materials can be as practical applications green material. The invention of green material can effectively reduce the cement usage amount, lower carbon emissions and environmental impact (Ian,Wang 2020).

However, many studies indicate that GGBS was used as a main cementitious material for cement reduction. The main function of GGBS is that it has a stable particle structure due to high temperatures quenching during the steelmaking process. However, GGBS cannot be used as a cement material which can trigger a hydration reaction with water molecules. Therefore, it needs to rely on a strong alkaline solution to stimulate the internal activity of the material to produce calcium silicate hydrate (CSH gel) or calcium aluminate hydrate (CAH gel) and monosulfide calcium aluminate hydrate (AFt gel), etc. The above-mentioned compound components will hydrate cementitious and fill the pores, increasing the strength, water tightness, compactness and durability of concrete (Gallucci 2013).

The addition of admixtures lead to UHPC has superior performance. Admixtures can be divided into two categories: mineral and chemical admixtures (Zhang 2022). The mineral admixtures such as fly ash, GGBS and silica ash, etc. are added in concrete will improve the workability, density, reduce hydration heat and emissions of greenhouse gas, etc., and because it contains a large amount of silica, It will consume alkali compounds in concrete and can reduce the adverse reactions of alkali aggregates. On the other hand, superplasticizers can be used as chemical admixtures because superplasticizers are surface active agents that have good dispersion and can improve the workability of cement materials. Therefore, superplasticizer is an important chemical admixture that can cause high slurry fluidity of UHPC. When superplasticizers are not used, it has better fluid behavior in low-alkali cement than higher-alkali cement. The workability gradually increases by adding more contents of superplasticizer. However, excessive use it will cause severe bleeding and segregation of concrete, which will delay the setting time for a longer time.

The workability of concrete material will be one of the important standards that can be vigorously promoted in general practice engineering. To avoid early hardening during transportation, or to facilitate pumping and construction, this study will discuss on retarding effect and improving fluidity of material.

2. EXPERIMENTAL PROGRAM

The replacement of cement with GGBS was designed different water/cement rations, such as 0.20 and 0.25 in this study. The sodium silicate and sodium hydroxide were mixed to alkali solution. The alkali excitation contents of 4%, 5%, and 6%, molecular rations of 0.4, 0.5 and 0.6 were designed in the experimental program. The 5×5×5cm3 cube specimens were performed 7- and 28-day compressive test, respectively. The results of workability, activity index and solution temperature were discussed for the reaction mechanism of alkali excitation effect.

2.1 Materials

1. Cement

Ordinary Portland type I cement was used in this investigation. The chemical properties of the cement as provided by the manufacturer, are given in Table. 1

2. Ground granulated blast furnace slag (GGBS):

The grade of GGBS is F100 water-quenched blast furnace powder. It has a specific gravity of 2.89 and a specific surface area of 4250 cm2/g. The activity index is greater than 95% for 28 days. The chemical proportion of silica, aluminum oxide and calcium oxide account for 88.72% of the total components. Hydration reactants of cement clinker will be formed after being activated by alkali, which will have the same characteristics of hydraulic hardness and setting properties as Portland Cement. The chemical properties of the GGBS as provided by the manufacturer, are given in Table. 1

Table. 1 Chemical proportion of cement and GGBS (Yuan 1987)

	Cement	GGBS
Oxide	Percent (%)	Percent (%)
SiO_2	21.04	34.58
Al_2O_3	5.46	13.69
Fe_2O_3	2.98	0.44
CaO	63.56	40.67
MgO	2.52	7.05
SO_3	-	0.56
others	4.44	3.01
total	100	100

3. Silica fume:

Silica fume is an amorphous polymorph of silicon dioxide. It is an ultrafine silica powder with an average particle diameter of 150 nm, 940U Type. Its material characteristics: blue-grey color, silica content is greater than 90%, moisture content is less than 1%, and loss on ignition is less than 3%. In Fig. 1, the composition of GGBS and cement are very close, and they have both cementation and pozzolan reaction characteristics. It can be evenly filled between cement particles because its finer than cement. Hence, the smoothness of concrete surface can be improved.

The fineness of this material is finer than cement, so it can be evenly filled between hydrated particles, which increasing the generation of CSH gel can improve the smoothness of the concrete surface, in the meantime, the early and final strength of concrete can be promoted. Increasing density of concrete, improve separation, bleeding phenomenon, impermeability and chemical corrosion resistance of concrete, so it is excellent filler.

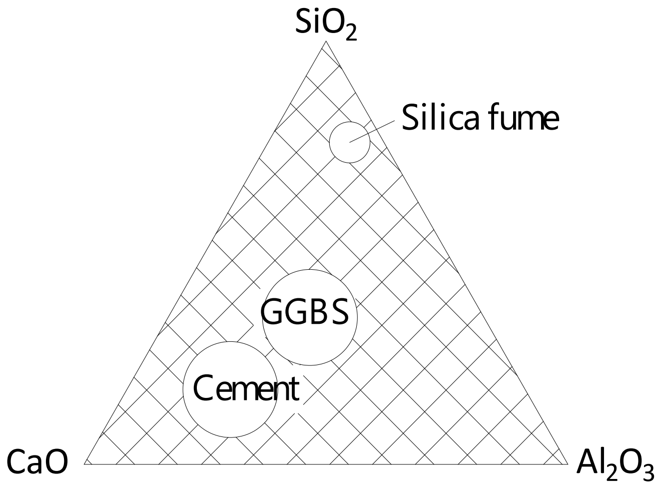

Fig. 1 CaO–Al_2O_3–SiO_2 ternary diagram of cement, GGBS and silica fume (Yuan 1987)

4. Silica sand

Silica sand is a hard, wear-resistant, chemical stability of silicate minerals, the main mineral component is SiO_2, Mohs hardness 7, no end management of brittle, conchoidal fracture, oil sheen, the relative density 2.65, insoluble in acid, Specific gravity: 2.55 ~ 2.65, uniformity coefficient: 1.5 or less, silicon dioxide: 99% (Yuan 1987). The quartz sand of two particle sizes were used as aggregates. The average particle size is 250μm. The densest packing ratio of the two is about 6:4 according to analysis.

5. Sodium silicate (Na_2SiO_2):

The alkali activator used a commercially available sodium silicate (water glass or liquid glass). This study uses sodium silicate containing 63% SiO_2 and 18% Na_2O. It is a white powder and is easily soluble in water. Stirring with water well, the solution is alkaline and can polymerize the alkali glue material.

6. Sodium hydroxide (NaOH):

Sodium hydroxide also known as caustic soda, commonly known as lye, the chemical formula is NaOH. It is a highly corrosive strong alkali. Generally it can be deposited as white flakes or granules, also dissolved in water to form an alkaline solution in environment of room temperature. It has a deliquescent property which also absorbs acidic gases of carbon dioxide and sulfur dioxide. A commercially available solid powder NaOH with 98% purity was used in this study. Processing of mixing with water to the required proportion will cause the release of high heat, so it must be stores quietly in a clean acid-proof and alkali-resistant container until room temperature for use. The main purpose of the alkali activator solution is to produce more silicone colloids for the low active materials, thereby hardening and strengthening the materials.

7. Superplasticiser (SP):

20~22cm for the water/cement ratio of 0.20 and 0.25 respectively. The workability of the fresh UHPC for the water/cement ratio of 0.2 is relatively reduced with higher alkali equivalent weight. The workability was 14~16cm, 13~14cm and 12~15cm for distinct alkali activator contents of 4%, 5%, and 6%, respectively.

In general, the workability is greatly improved between 16~17cm in the lower alkali activator content under water/cement ratio 0.25. The workability is declining, but they are still 14~16cm as more alkali activator content. Therefore, it shows that workability is poor and reduced with lower water/cement ratio, which will cause difficult problems to implement in practice concrete engineering in future.

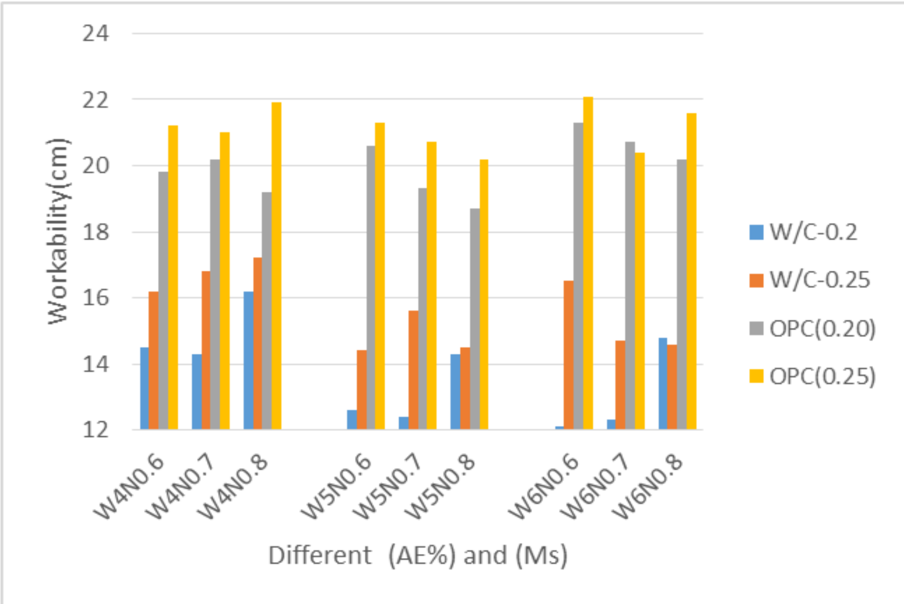

Fig. 4 Workability comparison of UHPC for distinct alkali activator contents and water/cement ratios.

3.3. Performances of the solid UHPC

In this study, the water/cement ratios of 0.20 and 0.25 were designed in UHPC mix proportions. The partially cement was substituted by GGBS to mix proportions and details of the mixes are shown in Table. 3 and 4. The compressive strength test results of UHPC (water/cement=0.20) for the partially cement was substituted by GGBS are shown in Fig. 5 It was found that 50% cement was substituted by GGBS (R50C50), 7-days compressive strength was approximately 70.82% of OPC. The strength is only about 7% of OPC as the substitution amount getting higher to reach 100% (R100). The 28-days strength performance of mix (R50C50) is 93.28% of OPC, which is roughly equivalent. The strength of mix (R62.5C37.5) decreases rapidly, only 63.44% of OPC. The strength of mix (R75C25) increases slightly. The strength of the R100 is only about 9.03% of OPC under the condition of no alkali excitation.

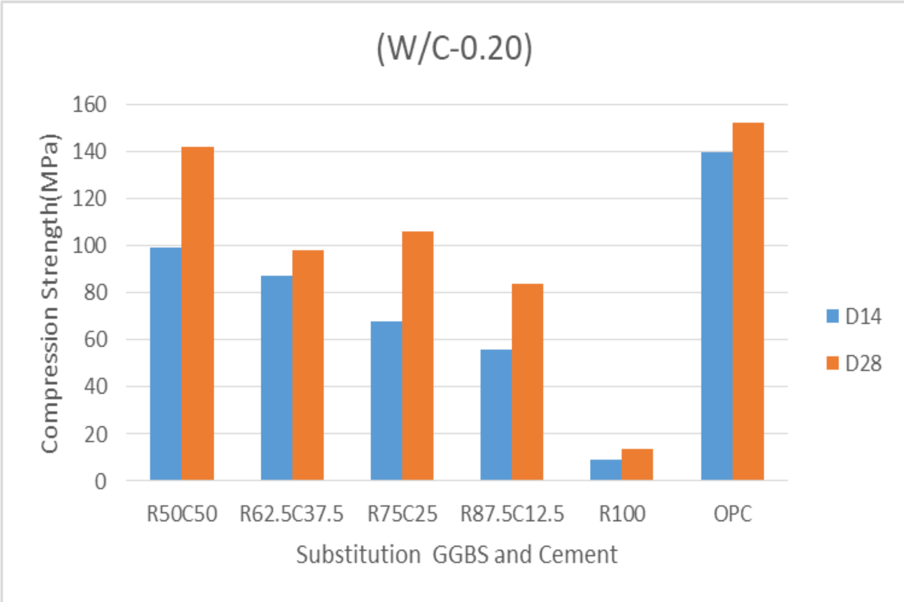

Fig. 5 Compressive strength test results of UHPC (water/cement=0.20) for the partially cement was substituted by GGBS

Furthermore, the compressive strength test results of UHPC (water/cement=0.25) for the partially cement was substituted by GGBS are shown in Fig. 6 The 7-days compressive strength is approximately 85.88% of OPC. As the mix proportion of substitution reach 100% (R100), the strength is only about 3% of OPC. It almost has 91.01% of OPC as mix (R50C50) proportion for 28-day compressive strength. The strength of the mix (R62.5C37.5) and (R87.5C12.5) proportion are 63.44% and 42.48% of OPC respectively. Mix proportion (R100) under the no alkali excitation condition, the strength is only about 6.38% of OPC.

Based on the above description, the results pointed out that the hydraulic reactivity is stable developed well on high water/cement ratio, but compressive strength development slowly. It is recommended that the mix proportion (R50C50) can be used for the advanced study of strength development. On the contrary, the strength of mix proportion (R100) without alkali excitation cannot meet the strength required in infrastructure construction. Therefore, the alkali activated challenge will be conducted in subsequent analysis.

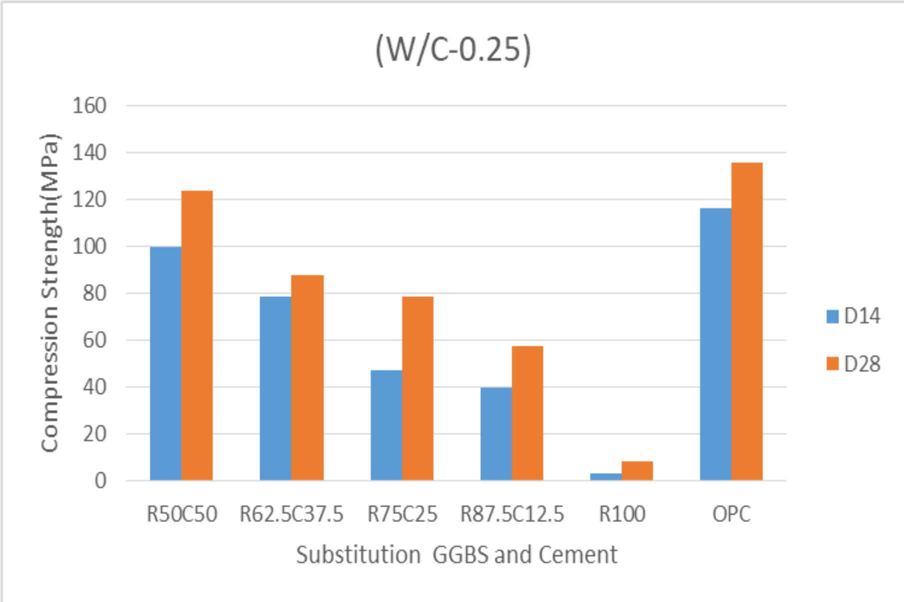

Fig. 6 Compressive strength test results of UHPC (water/cement=0.25) for the partially cement was substituted by GGBS

Fig. 7 shows the 14 and 28-days strength of mix (R100) proportion on water/cement 0.2. The compressive strength tests were performed on cubic specimens according to ASTM C109 standard at the age of 14 and 28-days. The 14 and 28-days compressive strength of OPC were 139.89 MPa and 152.35 MPa respectively. The 14 and 28-days strength of specimen with alkali activator contents of 4% were 101~121 MPa and 113~129 MPa respectively. The strength reduced to -12.95% and -15.13% than OPC at the age of 14 and 28-days. The strength was promoted 6.2% from 14 to 28-days. It explains the mechanism of alkali excitation and the strength rises slowly. But the compressive strength reaches to approximately 85% of OPC.

In view of this, it shows that the excitation concentration increases and the hydraulic reactivity is strong with the larger alkali activator contents. Finally, it is known that the compressive strength can be close to OPC.

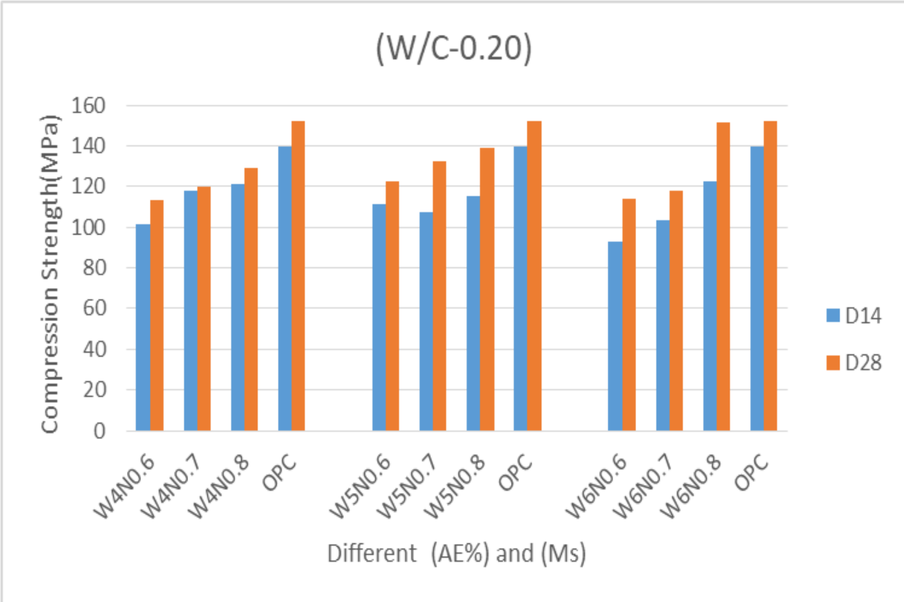

Fig. 7 Compressive strength comparison of UHPC for distinct alkali activator contents and water/cement ratio of 0.20

On the other hand, Fig. 8 shows that the 14 and 28-days compressive strength of OPC (water/cement=0.25) are 116.44 and 135.96 MPa respectively. The 14 and 28-days strength of specimen with alkali activator contents of 4%, 5%, 6% were 84~102 MPa and 90~125 MPa, 94~112 MPa and 119~124 MPa, 82~100 MPa and 90~111 MPa respectively. The strength of specimens with alkali activator contents of 4%, 5%, 6% reduced to -12.07% and -7.4%, -18.9% and -8.1%, -13.79% and -17.78 than OPC at the age of 14- and 28-day. By the alkali activator contents of 4%, 5%, 6%, the strength was just promoted 4.67%, 10.8%, 3.99% from 14 to 28-days respectively than higher water/cement OPC. The strength reaches to approximately 92%, 92%, 82% of OPC respectively.

The development of alkali excitation was limited by the amount of mix water. The compressive strength development of specimens is higher under alkali activator higher content and lower water/cement, 0.2. The strength reaches to approximately 99% of OPC. Otherwise, the strength development is lower under higher water/cement, 0.25 and alkali activator content, just only 82% of OPC.

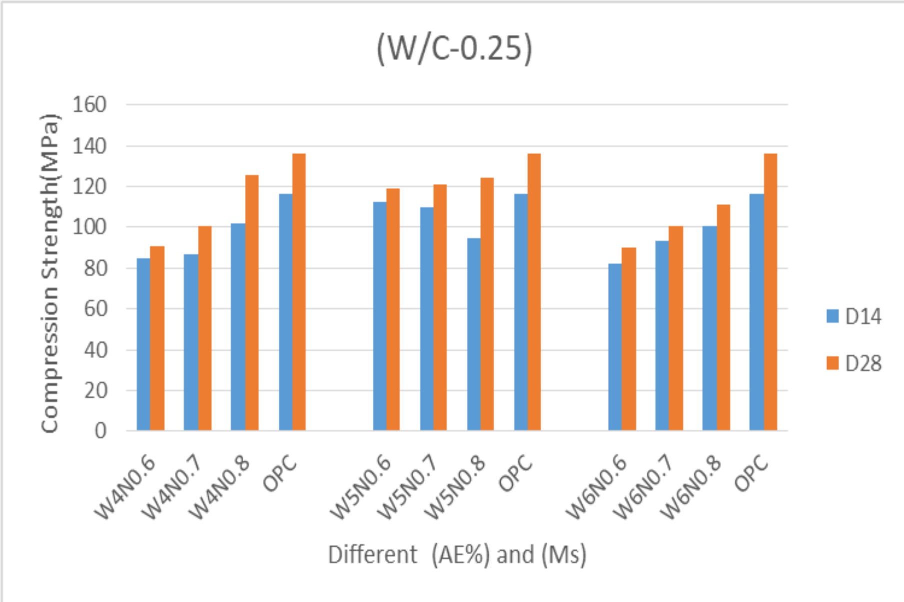

Fig. 8 Compressive strength comparison of UHPC for distinct alkali activator contents and water/cement ratio of 0.25

Pozzolan activity analysis is defined by ASTM C618, ASTM C311 and EN 450-1. Strength Activity Index (SAI (%)) is the ratio of the compressive strength of alkali-activated UHPC mortar and control cement mortar after curing for 28 days, as shown in Eq. (1).

The grade F100 GGBS was used in this study. Fig. 9 shows the SAI analysis results of the alkali activated GGBS specimens. The SAI of specimens with water/cement, 0.2 and alkali activator contents of 4%, 5%, 6% were 74~84%, 80~91%, 74~99% respectively. Otherwise, water/cement is 0.25, the SAI of specimens were 66~92%, 80~91%, 66~81% respectively. The literature indicated that the SAI above 85% indicates a great activity index (Martina 2023). Therefore, the alkali activator contents of 4%, 5% are recommended use under water/cement 0.2 and 0.25 respectively.

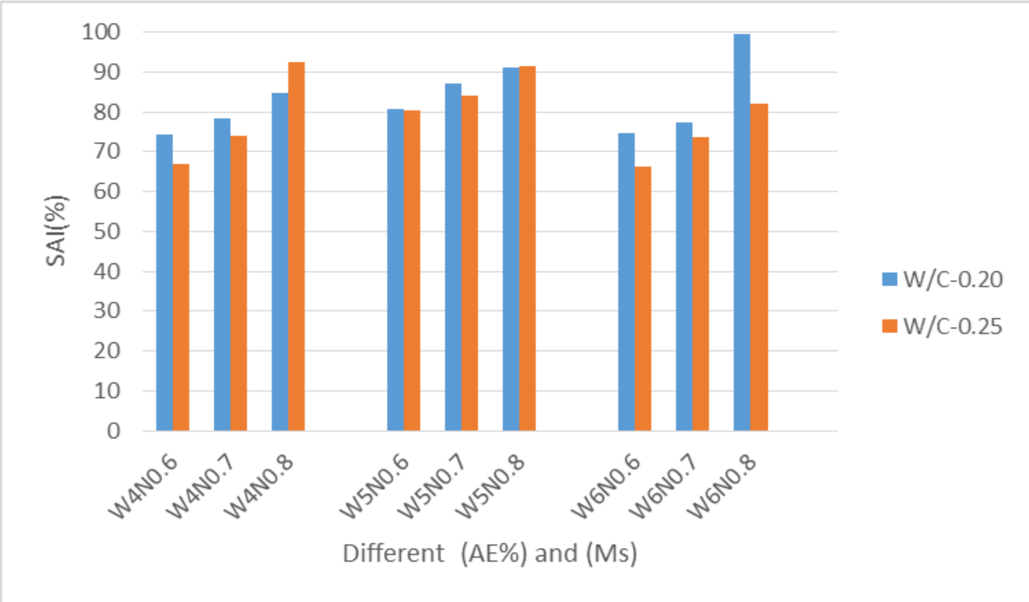

Fig. 9 Strength activity index of UHPC for distinct alkali activator contents and water/cement ratios

4.CONCLUSIONS AND SUGGESTIONS

This study has found the following conclusions, which are specially provided a reference for subsequent advanced research and development:

1. The 28-days compressive strength of UHPC specimens mix R50C50 with water/cement 0.20 and 0.25 can reach 93% and 83% of OPC respectively. Therefore, the strength decays rapidly as more and more substitution of cement. An alkali activator can be recommended used to strengthen the hydration reaction of GGBS.
2. The workability of the fresh UHPC were 12~13cm, 16~17cm for the water/cement ratio of 0.20 and 0.25 respectively. Workability is relatively reduced under higher alkali concentrations and lower water/cement; otherwise, it is improved under opposite of conditions. This indicates that it is difficult to implement in practice concrete engineering for poor workability of alkali excitation under lower water/cement.
3. The compressive strength development of specimens is higher under alkali activator higher concentrations and lower water/cement, 0.2. The strength reaches to approximately 99% and only slightly lower 0.58% of OPC for the hydration reaction strong; Otherwise, the strength development is lower under higher water/cement, 0.25 and alkali activator content, just only 82% of OPC. It indicates the higher strength performance in the case of low water/cement ratio and higher alkali excitation concentrations; otherwise, it is poor under opposite of conditions.
4. The SAI of specimens with water/cement, 0.2 and 0.25 were 74~99% and 66~92% respectively. The literature indicated that the SAI above 85% indicates a great activity index Martina (2023). Therefore, the alkali activator contents of 5% is recommended better usage.
5. Literatures suggest that the mixing temperature should be below 40℃(Xiaohong

2024). Therefore, the too high temperature of the alkali activated solution may promote the rapid hydration reaction. It will reduce the tightness and compactness of the structure.

REFERENCES

Coffetti, D., Crotti, E., Gazzaniga, G., Carrara, M., Pastore, T., and Coppola, L. (2022), "Pathways towards sustainable concrete", *J. Cem. Concr. Res.*, **154**, 106718

Cadavid-Giraldo, N., Velez-Gallego, M.C., and Restrepo-Boland, A. (2020), "Carbon emissions reduction and financial effects of a cap and tax system on an operating supplychain in the cement sector", *J. Clean. Prod*. 275.

Khajuria, A. et al. (2022), "Accelerating circular economy solutions to achieve the 2030 agenda for sustainable development goals", *Circ. Econ.*, **1**, 100001

Li, J., and Xu, G. (2022), "Circular economy towards zero waste and decarbonization", *Circ. Econ.*, **1**, 100002

Ian, H., Oliver, R., Judit, K., Sheikh, Z., Thibaut, A., Michael, O., Martina, O., Sophie, L., Irene, F., Nora, S., and Natacha, N. (2020), "Global status report for buildings and construction", *Uni. Nat. Environment Prog.*

Wang, H.Y., Chen, B.T. and Kou, C.W. (2020), "Effect of durability of High Fluidity Alkali-Activated Slag Concrete (HFAASC) with different liquid-solid ratios", *J. Chi. Corr. Eng.*, **34**(1), 24-30.

Gallucci, E., Zhang, X., and Scrivener, K.L. (2013), "Effect of temperature on the microstructure of calcium silicate hydrate (C-S-H)", *J. Cem. Concr. Res.*, **53**, 185-195

Zhang, X.Y., Yu, R., Zhang, J.J. and Shui, Z.H. (2022), "A low-carbon alkali activated slag based ultra-high performance concrete (UHPC): Reaction kinetics and microstructure development.", *J. Clean. Prod.*, **363**, 132416

Yuan, r., Gao, Q. and Ouyang, S. (1987), "Study on structure and latent hydraulic activity of slag and its activation mechanism", *J. Wuban Uni. Tech.*, **3**, 297-303

Martina, S., Rostislav, S., Franti, S., Kl´ara, P., Petr, F., and Roman, S. (2023), "Pozzolanic activity of stockpile ash: Comparison of test methods", *Case Studies in Cons. Mat.*, **19**, e02396

Xiaohong, Z., Zhe, Z., Mingyu, L., Kai, Y., and Jiaqi, L. (2024), "Temperature-sensitively dissolving of GGBS in neutral and alkali media", *J. Constr. Build. Mater.*, **418**, 135353

Chao, Z., Weidong, S., Abbas T., Jianxin F., Tianyu Z., and Yuye T. (2024), "Hydration mechanism and mechanical-thermal correlation of cemented paste backfill under different curing temperatures", *J. Bui. Eng.*, **85**, 108691