RESEARCH ARTICLE OPEN ACCESS

Self-compacting concrete's new and hardened qualities when metakaolin and GGBS are used in place of cement

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Date of Submission: 02-01-2018 Date of acceptance: 15-01-2018

ABSTRACT

Self-compacting concrete (SCC) is a contemporary high-performance concrete that uses a lot of cement but performs exceptionally well in terms of filling and flowing. These days, a variety of substitute materials, including as metakaolin (MK) and ground granulated blast furnace slag (GGBS), can be utilized in place of cement to mitigate the drawbacks associated with its use. The purpose of this study was to examine the fresh and hardened properties of SCC made by GGBS and MK as a partial substitute for cement. MK was used to replace cement at a consistent level of 10%, while GGBS was used as a ternary blending powder to replace cement at different levels of 15%, 20%, 25%, and 30%. In contrast to the findings for GGBS, which showed an improvement in workability, the results show that the additional MK decreased workability. The mix that contained MK improved the strength characteristics of the hardened properties at an early age, while the mix that had both MK and GGBS performed better at a later age. According to the results of this study, 10% and 25% cement replacement, respectively, are the ideal levels for producing high-quality SCC for MK and GGBS.

Keywords: *Self Compacting Concrete, Metakaolin, Ground Granulated Blast Furnace Slag, Workability*

I. INTRODUCTION

Self-compacting concrete (SCC) is a contemporary type of high-performance concrete that can fill formwork with heavy reinforcement at constant homogeneity without any migration or separation of its large mechanism. It can also flow and compact under its own weight without the need for external vibrations ***(Dadsetan & Bai, 2017).*** Okamura first put up the idea of SCC in the 1980s, and Ozawa at the University of Tokyo in Japan created the prototype in 1988. To solve the issue of unskilled labor in the construction industry, it has been used for underwater concreting and the construction of heavily reinforced structures. It eliminates the need for vibration, speeds up construction, lowers labor costs, and reduces noise ***pollution (Shi, Wu, Lv, & Wu, 2015; Vivek & Dhinakaran, 2017).*** The first mix design for SCC as a universal approach was put forth by Okamura and Ozawa in the late 1990s [6].

Aspects of the design process included fixing the fine aggregate (FA) volume at 40% of the mortar volume and setting the coarse aggregate (CA) volume at 50% of the solid volume of the concrete. The fluidity tests on mortar and concrete are used to determine the water/binder (W/B) ratio and the dosage of super-plasticizer (SP) [1]. Trials are conducted on a concrete basis using these ratios to determine the final mix composition ***(Okamura, 1997).*** From the perspective of making SCC a standard concrete, ongoing research has been conducted to develop a logical mix-design approach and self-compatibility testing techniques ***(Okamura & Ouchi, 2003).*** In practice, the SCC is considered satisfied when specific measurements pertaining to the concrete's workability and flowability meet the standards outlined in the SCC guidelines ***(Efnarc, 2002).*** High cement volume, low CA concentration, and SP to lower the water to binder ratio are the ingredients of self-compacting concrete. Due to the significant need for cement in the production of SCC, substitute materials are needed to promote environmentally friendly and sustainable building materials by lowering carbon emissions [2]. These days, new generation concrete with a lower carbon footprint and greater efficiency is made using alternative cementitious materials like fly ash, silica fume, metakaolin (MK), ground granulated blast furnace slag (GGBS), and limestone powder [3].

The environmentally friendly, ultra-fine white substance known as "metakaolin" is made from kaolin clays by heat-treating them without producing carbon dioxide (CO_2). Under controlled circumstances, one of the most prevalent natural minerals can be found at extremely high temperatures, between 650 and 900 C. The ideal cement substitute, MK typically comprises 50–55% silicate (SiO_2), 40–45% aluminates (Al2O_3), and other oxide particles in trace amounts, such as iron oxide (Fe2O3), titanium oxide (TiO2), calcium oxide (CaO), and magnesium oxide (MgO). The size of MK particles ranges from 1 to 2lm. By calculating the CO_2 emission, ***Vejmelkova, Keppert, Grzeszczyk, Skalinski, and Cerny (2011)*** and Kavitha, Shanthi, Arulraj, and Sivakumar (2016) investigated the impact of MK and OPC on SCC and demonstrated that the MK produces [4] .

When compared to cement, MK's primary drawback is its high production costs ***(Badogiannis, Sfikas, Voukia, Trezos, & Tsivilis,*** 2015). However, its low production rates now may be the primary cause of this (Kapoor, Singh, & Singh, 2016). Compared to other fillers, MK can fill cement paste pores more effectively and generate concrete with greater strength at younger ages. It has been discovered that the addition of MK alters the rheological behavior of SCC. MK significantly impacted the transition zone's microstructural strength. The water content and SP dosage in mortar and concrete are increased by increasing the MK content. Because MK has greater pozzolanic reactivity at early ages, its usage in concrete may enhance the mixture's viscosity (Melo & Carneiro, 2010) and early strength ***(Ghoddousi & Saadabadi, 2017).*** According to the average results of RCPT and chloride diffusion, MK had a 2.25- and 4.25-fold stronger impact on chloride permeability in terms of durability resistance than the water-to-binder ratio and total binder content, respectively ***(Abouhussien & Hassan, 2015)*** [5]. A by-product of the steel or iron industry's blast furnaces is GGBS. Additionally, GGBS is a non-metallic substance that is created in a blast furnace while iron is molten. It is mostly composed of calcium silicates and aluminosilicates as well as other bases (***Dadsetan & Bai, 2017***).

Approximately 250 million tons of GGBS are produced annually worldwide. Just 90 million of these are utilized to make concrete (***Boukendakdji, Kadri, & Kenai, 2012***). Although a study indicates that the strength between 28 and 90 days also rose, the early age strength gains from concrete containing GGBS increased as the percentage of GGBS in the concrete increased (Samad & Shah, 2017). Furthermore, GGBS encourages sustainability by improving the fresh and toughened qualities of SCC. Concrete gains strength over time because of GGBS's ability to slow down the setting process. According to Altoubat, Badran, Junaid, & Leblouba (2016) and Dadsetan & Bai (2017), concrete supplemented with GGBS can reduce heat generation during the hydration process and increase resistance against sulphate and chloride attacks, making it appropriate for marine applications. Conversely, GGBS improves tensile strength, elastic modules, higher surface finishes, and addresses the durability issue in the production of iron or steel [7].

II. EXPERIMENTAL INVESTIGATION

2.1: MATERIALS

The materials employed in this investigation include GGBS, CA, FA, MK, and ordinary Portland cement (OPC). San OPC of grade 42.5 cement was utilized in this study as the main binder, adhering to EN197-1 (2000) cement–part 1. In place of cement, which was acquired locally, MK and GGBS were utilized. The chemical and physical characteristics of OPC, MK, and GGBS are displayed in Tables 1 and 2. In accordance with BSEN 12620, CAs were crushed stone that could not exceed 12.5 mm in size and were utilized as FAs in rivers. CA and FA had specific gravities of 2.53 and 2.51, respectively. CA and FA absorbed water at rates of 0.95% and 1.24%, respectively. To help with workability, SP in liquid states was utilized. ADVAV R Cast-512, a polymer-based, high range water-reducing admixture without additional chloride, is the name of the SP that is being utilized. It is designed to meet the requirements for concrete chemical and mixes [8].

2.2: MIX PROPORTION

Six mixes in all, including a control mix, were created to meet the different levels of cement substitution by GGBS. A consistent 10% cement replacement rate by MK was applied to all the mixes. The total binder determines their positioning.

Oxide Contents (%)	Percentage Content	MK	GGBS
Calcium Oxide	61-68	1.3	41.26
Silicon Dioxide	18-26	53	35.71
Aluminium Trioxide	4-8	48	17.43
Iron Oxide	0.6-7	0.6	1.34
Magnesium Oxide	0.2-1.4	0.7	6.30
Alkalies	0.5-1.5	0.8	1.00
Sulphur Trioxide	1.4-3.0	0.9	1.00

Table No. 1: Chemical properties for MK and GGBS

Properties	**OPC**	**MK**	**GGBS**
Specific Gravity	3.17	2.55	2.8
Specific Surface Area	368.12	12000	399
Colour	Grey	white	off-white
Loss on Ignition	0.97	0.7	0.33

Table No. 2: Physical Properties of OPC, MK and GGBS

The state din is the mix proportion for each mix for 1 m3. Based on earlier research (Dinakar, Sethy, & Sahoo, 2013; Kavitha et al., 2016), Table 2 was carried out in accordance with (Efnarc, 2002) to prevent segregation or bleeding of the fresh concrete.MK was used to partially replace cement at a steady rate of 10% of the total binder. Furthermore, GGB Sat was used in place of cement at different percentages of 15%, 20%, 25%, and 30% of the total binder. While the water to cement ratio was set at 0.38 for all mixes, SP ranges from 1.0% to 1.5% [9].

2.3. TESTS ON FRESH PROPERTIES

To verify the novel qualities of the generated SCC, several tests were performed. Slump flow, T50 test, V-funnel, and L-box were the related tests that were employed. The slum pflow test was used to evaluate the flow ability (deformability) of SCC, per Efnarc (2002) and BSEN12350-2 (2009). Additionally, to evaluate the flow velocity and viscosity of SCC, the T50 test was conducted in tandem with the slump flow test. The T50cm test calculates how long it takes for concrete to reach a 500mm diameter. The T50cm falls between 2 and 5 seconds, whereas the permissible slump flow diameter is between 650 and 800 mm [10].

As suggested by Enforce (2002), the V-funnel test was used to evaluate the viscosity and filling capacity of SCC. Concrete is poured into a V-shaped funnel, and the amount of time it takes for the concrete to exit the funnel is measured and recorded as the V-funnel flowtime. V-funnel time should be within the permitted range of 6 to 12 seconds. The L-box test was used to evaluate SCC's passing ability in accordance with Enforce (2002). Without segregation or blocking, the flow was measured through tense apertures, such as the gaps between reinforcing bars and other obstacles. The L-box test's acceptable range falls between 0.8 and 1.0 of the blocking ratios (BR) [11].

2.4: TESTS ON HARDENED PROPERTIES

Using the suitable specimens recommended by BSEN12390-3(2009), the hardened properties of SSC were assessed by compression, splitting tensile, and flexural tests. A compression test machine was used to perform the compression test in accordance with BSEN12390-3(2009). A 100 x 100 x 100 mm cube specimen was used. 36 cubes in total were used to assess the compressive strength of all combinations over 7 and 28 days. The maximum sustained load was noted after the concrete cubes were loaded till; they failed [12].

An indirect technique for figuring out the concrete's tensile strength is the splitting tensile strength test. It tested cylinder specimens with a diameter of 100 mm and a height of 200 mm. The testing procedure followed BSEN12390-6 (2009). Thirteen and twenty-eight days of tensile strength tests were conducted on a total of thirty-six-cylinder specimens. A modulus of the greatest stress attained prior to the specimen yielding is the flexural strength. Flexural strength testing was done in accordance with BSEN12390-5 (2009) [13].

III. RESULT AND DISCUSSION

3.1: FRESH PROPERTIES RESULT OF SCC

Table 4 summarizes the findings of new properties tests of SCC that included GGBS and MK. According to the results, the manufactured concrete's fresh qualities fall within acceptable bounds. The flowability of SCC is assessed using the slump flow test. Figure 1 depicts the flowability state of one of the mixes during a laboratory test. Better flowability (deformability) of the concrete is indicated by a larger slump flow diameter, whereas less flowability is indicated by a smaller slump flow diameter. Efnarc (2002) states that a slump flow diameter of 650 to 800 mm is adequate. The slump flow measured in this investigation was between 680 and 720 mm, meeting the SCC minimum standard [14].

Figure No. 1: Slum Flow Test

The slump flow diameter for mix A1 (lowest flow diameter) was 680mm, whereas the slump flow diameter for control mix A0 (containing only OPC) was 690mm. It was observed that the flow diameter decreased by 1.5% when 10% MK was present. The addition of 10% MK resulted in a decrease in flow diameter even though the dosage of SP increased from 1.0% to 1.5%. This could be explained by the ultra-fine particle size of MK and the pozzolanic reactivity that caused the internal friction between the grains to rise. Thus, fluidity (deformability) is lost because of this friction. The flow time result for the T50cm test shows a similar pattern, with A1 requiring more time than A0 by 16.7%. This suggests that the addition of MK causes concrete to become more viscous, which lengthens the time it takes to attain a

500 mm diameter. extending the flow duration, which helps to extend the MK's response time and affect fluidity. In the same vein, adding MK causes the mixture's yield stress to rise. This indicates that it will take longer for the concrete to begin flowing. The non-Newtonian fluid behavior of MK may be the cause of the additional time needed for the mix containing MK [16].

The slump flow diameters for the combinations including GGBS, A2, A3, A4, and A5 were 700 mm, 710 mm, 720 mm (the larger flow diameter), and 685 mm, respectively. It was found that raising the replacement levels of GGBS improves the flowability (deformability) when compared to A0. This was demonstrated by the A_2, A_3, and A_4 mixes, whose percentage of flowability increased by 1.5%, 2.9%, and 4.5%, respectively, in comparison to A0. This may have something to do with the size of the GGBS particles. Compared to OPC and MK, its particle size is larger. Particle size increases result in a decrease in total surface area, which can improve flowability (deformability) and slow down the chemical reaction (sitting time) while maintaining a minimal level of CSH gel content. Additionally, the addition of GGBS to concrete mixtures containing larger particles reduces internal paste friction, which may also restore flow ability. Compared to A0, A5's flowability decreased by 0.7%, which could be related to the dosage of SP. For the GGBS mixes group, the SP dosage was set at 1.5%. This indicates that no SP part was considered for GGBS. Consequently, A5's fluidity loss is linked to SP dosage, which needs to be changed to preserve flowability. For A2, A3, and A4, the corresponding flow times at T50cm were 3s, 2.9s, and 2.7s. Concrete with a higher T50cm duration has a higher viscosity and less flowability. A4 achieved the lowest flow time at T50cm at 2.7s. By reducing the flow duration, it was shown that raising the GGBS level to 25% while maintaining a steady SP dosage could enhance viscosity. This pattern runs counter to what was seen in A1. Based on this discovery, GGBS improves flow time by reducing the time needed to reach 500mm diameter flow since its particles are larger than those of MK and cement. Furthermore, in comparison to MK or cement, GGBS has a lower yield stress, which reduces the internal force and requires less time to initiate the flow (Ge uneyisi, Gesoglu, & Ozbay, 2011; Ho, 2013; Madandoust & Mousavi, 2012; € Ozbay et al., 2016; Ramanathan, Baskar, Muthupriya, & Venkatasubramani, 2013; Uysal & Sumer, 2011; Yamuna & Krishna, 2017). This pattern shortens the flow duration while increasing the flow rate. The T50cm for A5 was 3.2 seconds. In comparison to A0, it was observed that the flow time at T50cm increased by 6.7% [18].

3.2: V-FUNNEL RESULT

The filling ability or viscosity of SCC was evaluated using the V-funnel test, and Figure 2 depicts the mix's state during the V-funnel laboratory testing. The concrete's increased viscosity and decreased filling capabilities are indicated by the longer V-funnel duration. The V-funnel time for mixture A0, the control, was 10 s. A1 attained the highest funnel duration of all, 11 s, which was a little increase. Two factors could be involved in the loss of filling ability: fineness and an increase in MK yield stress (Kavitha et al., 2015). The strong reactivity generated by the MK ultrafine particles speeds up the hydration process and raises the mixture's viscosity. Mixtures A2, A3, and A4 generated V-funnel times of 9s, 8.5s, and 7.5s, respectively [19].

Figure No.2: V-Funnel Test

A4 had the shortest funnel time, measuring 7.5 seconds. It was observed that by reducing the filling time, raising the GGBS replacement level by up to 25% could enhance filling ability. Because GGBS's particles are bigger than those of MK and cement, they help to minimize surface area, lower reactivity, and facilitate concrete movement (filling ability). According to ***Boukendakdji et al.*** (2012) ***and Dadsetan & Bai*** (2017), GGBS also has a reduced yield stress because it reduces the internal tension in the mixture, which aids in the concrete's increased fluidity. However, compared to another mix that contained GGBS, the funnel time for A5 was 11s, indicating a loss in fluidity. A small increase in the funnel time for 30% replacement cement by GGBS serves as evidence of this. A5's loss of filling ability demonstrates that, for the same SP content, up to 30% of GGBS can negatively impact concrete consistency. It can be inferred that GGBS improves consistency when it is substituted up to 25% of the time while maintaining a steady water to binder ratio [19].

3.3: L-BOX RESULT

As seen in Figure 3, the L-box test was used to evaluate SCC's passing proficiency. The capacity of the concrete to pass through the congested reinforcement steel without segregation or obstruction is known as passing ability. The L-box, which is displayed as BR, measures passing ability. The concrete mix's stronger passing ability is shown by its higher BR value. The BR findings fall within the acceptable range suggested by EFNARC, ranging from 0.84 to 0.94. For every blend, there is no indication of blocking or segregation. For A0 and A1, the corresponding BR values were 0.88 and 0.84 [20]. The presence of MK, which may impair passing ability, is the cause of the reduction. It may be seen that inclusion MK reduces passing ability due to a loss in fluidity, which is also what Kavitha et al. (2015) found. Additionally, A2, A3, and A4 had BR values of 0.89, 0.92, and 0.94, respectively. In comparison to A0, the BR increments for A2, A3, and A4 mixes were 1.15 percent, 4.6%, and 6.8%, respectively. These findings demonstrate that GGBS can offset the decrease caused by MK. The GGBS particle size may be linked to the improvement in passing ability since it reduces internal friction, which in turn improves fluidity and possibility. However, for A5, BR was lowered to 0.85; it was observed that when 30% of GGBS was substituted for cement, the passing ability declined. It shows that up to 25% of GGBS is the ideal level to give a strong passing capacity of SCC. The outcomes of BR were consistent with the findings of ***Bouk Endakdjietal (2012) and Dadsetanand Bai (2017).***

IV. HARDENED PROPERTIES RESULT OF SCC

Compression strength, splitting tensile strength, and flexural strength are the toughened characteristics noted in this investigation. Table 5 displays the findings of the average hardened properties summary. Concrete's compressive strength is usually a good indicator of its performance. Figure 4 displays the control mix A0's compressive strength findings after 7 days, which were 45 MPa.

Figure No. 4 – L-Box Test

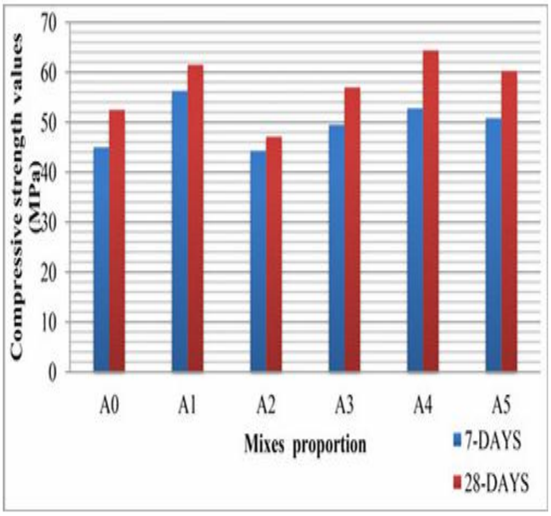

Figure No. 5 – Compress Strength Value

Out of all the mixes at the same age, Mix A1 produced the maximum strength, 56.3MPa. The addition of MK to the mixture increased its strength. Because MK is a powder blend of various binder grains, it reduces capillary holes, improves the transition zone (the cohesiveness between the aggregates and cement paste), and provides efficient paste packing. Additionally, because MK is finer, the binder's total surface area increased, speeding up the chemical reaction process and reducing the setting time. However, MK has a lot of silicates and aluminates, which increases its reactivity and early development. This could then encourage the formation of calcium silicates hydrate (C-S-H) gel, which oversees the hydration's early strength development. Nevertheless, because C-S-H gel requires a significant amount of calcium hydroxide (CH) to increase strength, CH also has a negative impact on strength. The strength increased when MK was present because it might react with CH through a secondary reaction (Kavitha et al., 2015).

For both 7 and 28 days of age, the compressive strength is higher than A0 when GGBS is present, which is 20% to 30% in A3, A4, and A5. This might be the result of both the high reactivity of MK because of its fineness and the dual action of pozzolans inclusive to the combination, where a GGBS created filler or packing effect to the mix. The disparity in density between GGBS and OPC may also be connected to this. Therefore, adding an equal mass of GGBS increases the volume of the paste and improves the cohesive transition zone, both of which increases compressive strength. However, when comparing the mix containing 15% GGBS (represented by A2) to A0, no discernible difference in strength is found.

Conversely, as compared to mix containing MK alone, A1, the compressive strength of A2, A3, A4, and A5 is reduced. Both the 7-day and 28-day strengths showed a similar pattern. This results from both the sluggish reactivity of GGBS and OPC's decrease in the calcium hydroxide supply. Additionally, it was found that compressive strength was improved by up to 25% cement replacement with GGBS. Even though GGBS has a high silicate and aluminate content, its comparatively bigger particle size than MK contributes more to strength development by reducing the total surface area that regulates the reaction rate. These factors cause the setup time to increase and the hydration to slow down. As a result, compared to mixes without GGBS, the concrete containing GGBS exhibited poor strength at an early age (7 days) because the hydration process was delayed.

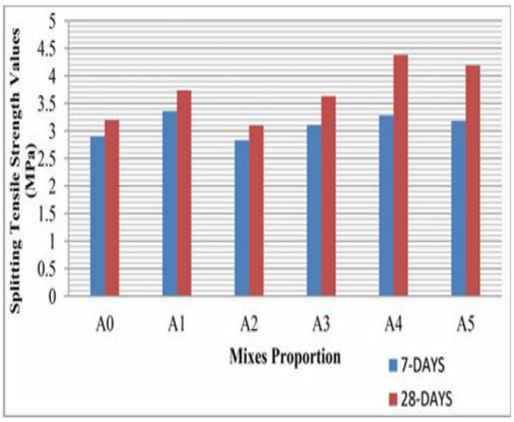

Figure No. 6 – Splitting Tensile Strength

Mixes A2, A3, A4, and A5 exhibit the contribution of GGBS to the tensile strength of SCC. For both ages of 7 and 28 days, the trend indicates an increase in tensile strength for all mixes except for A5. The pattern of growth of compressive strength is almost identical to this trend. A4 has a maximum tensile strength of 28 days and a strength of 4.38 MPa. The tensile strength of mix A5 is somewhat lower than that of its equivalent, mix A4. The A3, A4, and A5 mixes' splitting tensile strength increased between 7.2% and 13.1% and 13.4% and 37% for 7 days and 28 days, respectively, as compared to A0. Furthermore, A_2 produces the lowest splitting tensile strength after 7 and 28 days. Compared to the A_4, the splitting tensile strength of the A_5 was comparatively lower. It can be a result of OPC supplying less calcium hydroxide, which is necessary for the hydration of pozzolan minerals. SCC mixes continued to get stronger at 28 days of age. The results showed that the replacement level of GGBS has an impact on the development of splitting tensile strength of SCC mixtures.

It is evident that 25% GGBS substitution is the ideal level. This is because the iron property in GGBS content and the ongoing hydration process both contribute to the growing splitting tensile strength. On the other hand, the A5 mix's splitting tensile strength decreased at both 7 and 28 days of age. The iron component in GGBS, which helps to improve splitting tensile strength, particularly at greater replacement levels, may be the reason why the strength of the 28-day mix was comparatively higher than that of the A1 mix. (Yamuna & Krishna, 2017; Vivek & Dhinakaran, 2017).

V. CONCLUSION

To achieve satisfactory fresh and hardened qualities of SCC, a ternary blending cement consisting of MK and GGBS could be used up to 35% of the time. Without segregation or bleeding, the fresh properties result for all SCC combinations meet the minimal criteria stipulated by Efnarc (2002). When compared to a typical SCC mixture, the use of MK as a cement substitute showed a decrease in fresh qualities such flowability, filling ability, and passing ability. Still, the outcomes fall within SCC's acceptable range. The size of the MK particles, which fall into the ultra-fine category, and their increased pozzolanic reactivity could also be factors. The internal friction between the grains then increased as a result. Consequently, the loss of fluidity (deformability) brought on by this friction raises the viscosity at the same time. By adding GGBS to the SCC combinations, the fresh characteristics were enhanced and the capacity to offset the decline caused by MK in fresh states was increased.

Except for A_2, all SCC mixes performed better than control mixture A0 in terms of toughened characteristics. Due to its stronger pozzolanic reactivity than any other mixture, A1 exhibited higher compressive strength and splitting tensile strength at an early age (7 days) when MK was used as the only cement substitute. In comparison to regular concrete, the strength of concrete containing both GGBS and MK is improved in A_3, A_4, and A_5 after seven and twenty-eight days. Comparing A_2 and A_3 concrete to A1 concrete that solely contains MK, however, results in a decrease in strength. This results from GGBS's filling/packing action and MK's high reactivity, both of which support the early development of strength. Delaying GGBS reactivity subsequently aids in the development of strength at a later age. However, when two different kinds of pozzolans are present, the need for calcium hydroxide may be more than what the OPC can provide, which weakens the subsequent comparison.

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