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Classification of Alkali Activated GGBS Mortar According to the Most Suitable Usage at the Construction Site

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The usage of OPC-free alkali activated ground granulated blast furnace slag(GGBS) mortar has been widely studied on the previous years, due to its advantages on sustainability, durability and workability. This paper brings a new view, aiming to classify the best application in situ for each mortar, according to the type and activator content. By this practical implication, more efficiency is achieved on the construction site and consequently less waste of materials. In order to compare the different activators, the following experiments were performed: analysis of compressive strength at 28 days, setting time measured by needles penetration resistance, analysis of total pore volume performed by MIP and permeability assessment by RCPT test. In general, activated GGBS had acceptable performance in all cases compared to OPC, and remarkable improved durability. Following the experimental results, it was confirmed that each activator and different concentrations impose distinct outcome performance to the mortar which allows the classification. It was observed that the activator $Ca(OH)_2$ is the most versatile among the others, even though it has limited compressive strength, being suitable for laying mortar, coating/plaster, adhesive and grouting mortar. Samples activated with NaOH, in turn, presented in general the most similar results compared to OPC.

Keywords : GGBS, Chemical activators, OPC free mortar, Mortar classification, Efficient usage

1. INTRODUCTION

Concrete structures are the biggest part of national infrastructure projects worldwide. Therefore, their adequate performance in terms of durability has considerable relevance on the development degree of modern society(Grigg, 1988). However, civil and structural engineering are areas of knowledge still partially based on ancient techniques, and, due to numerous reasons confront the need of new technologies, that could directly affect the welfare and productivity of each country, in aspects of quantitative and qualitative management of resources. Among those reasons, the most concerning are the imminent lack of natural resources and the social damage due to severe environmental degradation in different regions and ecosystems. For instance, cement which is the main ingredient of concrete and mortar imposes risks, since its production is responsible for most of the CO_2 emissions in developed nations.

On this line, in order to find alternative “green materials” that could still optimize the construction processes and mitigate wastes at the construction site, this paper deals with the practical implications of using cement-free ground granulated blast furnace slag(GGBS) mortar. GGBS is a byproduct of steel and iron, and as for other types of industrial by-products, the wrong disposal of it imposes serious problems of toxicity for the environment, representing one more reason to find possible manners of reutilizing it. According to D. Suresh and K. Nagaraju(2015) GGBS is used to make durable concrete

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structures in combination with ordinary Portland cement and/or other pozzolanic materials. The major use of GGBS is in partially mixed concrete where GGBS usually replaces about 50%, but sometimes up to 70% of the normal Portland cement concrete. As reported by D. Suresh and K. Nagaraju(2015) the higher the portion, the better is the durability. The main technical benefits GGBS provides according to the authors are better workability, high resistance to chloride ingress, considerable sustainability benefits, high resistance to attack by sulphate and other chemicals, lower early age temperature rise.

One of GGBS's disadvantages is that it is not available for smaller-scale concrete production because it can only be economically supplied in bulk. Another disadvantage, as observed by K. Eguchi(2011), is that GGBS concrete, when comparing to ordinary Portland cement concrete, has lower initial strength and higher dry shrinkage. Moreover, the absence of C_3S or C_2S in GGBS retards the hydration reactions (lack of alkalinity) and the mortar mixing need an unrealistic period of time to harden. To try to overcome these possible performance drawbacks, the utilization of chemical activators has been largely proposed. The most commonly used activators are alkalis, silicates and alkaline sulphates. Depending on the activator choice, the hydration process can be faster or slower due to different chemical characteristics such as solubility and ionization capacity. On this paper, the choice was made for alkali activators, namely KOH, NaOH and $Ca(OH)_2$ at 0.5%; 1.0%; 1.5% and 2.0% by mass of binder.

However, different from previous works, on this paper the main goal was not only to evaluate the acceptable performance of activated GGBS mortar but to further discuss its use considering in which cases it can be more efficient, because for example, according to Souza et al(2014) mortar losses at the construction site are not physically negligible, accounting to 102% for plaster in interior places, 53% for exterior places and 42% for subfloor. By the appropriate use of alkali activated GGBS, according to the type and activator concentration, different characteristics are obtained and this versatility provides the possibility of classifying each according to the best function, having as a consequence less waste of materials.

2. EXPERIMENTAL METHODS

2.1 Activated GGBS

GGBS is produced from the blast-furnaces of iron and steel industries and it is very useful in the design and development of high quality cement paste, mortar and concrete. The chemical composition of GGBS, which can be directly related to the production process and storage time, remarkably influences its reactivity. For example, long periods of storage can cause a significant loss on chemical properties. Table 1 shows the chemical composition and the fineness of GGBS produced in South Korea, for example. The chemical composition, particularly the relative percentage of oxides represents the main factor on reactivity and thus on hydraulic properties, which is a critical parameter for a binder. Moreover, as it was previously mentioned, alkali activators, namely KOH, NaOH and $Ca(OH)_2$ at 0.5%; 1.0%; 1.5% and 2.0% by mass of binder were used on the mix to maintain alkalinity and avoid delay of hydration reactions and hardening.

Table 1. GGBS produced in South Korea

Binder	Oxides composition(%)						Fineness (cm^2/g)
	SiO_2	Al_2O_3	FeO	CaO	MgO	SO_3	
GGBS	34.20	11.70	1.40	41.20	3.70	1.70	4290

2.2 Setting Time

In order to verify quantitavely the hydration reactions and hardening of alkali activated GGBS mortar, the setting time was measured. The method utilized to determine the setting time by needles penetration resistance of fresh mortar. At first the mortar in the fresh state was poured in a container of 150mm of lateral dimension and height. The time at which the cement begins to lose its plasticity is called the initial setting time and the final setting occurs when plasticity is completely lost. The time of initial and final setting were fixed according to ASTM C403M-16, for when each of the penetration resistances reached 3.4 and 27.5MPa(kg/cm^2), respectively. As a consequence, the workable time, period in which the mortar can be still be handled at the construction site, was obtained by the difference between initial and final setting.

2.3 Compressive Strength

To evaluate compressive strength, one of the most important characteristics at the hardened state, mortar cubic specimens sized 50mm x 50mm x 50mm were prepared, according to recommendations of KS F 2405(2010). The mix design, related to the proportion of binder, for water and sand(density: 2.58) respectively was as follows: 1.00 : 0.40 : 2.45, for all samples. The curing temperature, after demolding, was kept at 20 ± 2℃. Lastly, development of compressive strength was measured at 7, 14, 28, 56, and 91 days, however for this paper only the compressive strength at 28 days will be displayed to provide a clear view of results at the most important age when taking into consideration mortar functions.

2.4 Porosity

For some of the usages of mortar, such as external plaster, durability represents an important factor. Therefore, to determine the pore structure of GGBS activated mortar and its permeability, mercury intrusion porosimetry test was conducted. Specimens were prepared after 56 days of curing, being first oven dried to achieve the temperature of 50℃, for 24h. The measurement conditions consisted of a contact angle of 130˚, and Hg surface tension of 485dynes/cm. The pressure was converted to the equivalent pore diameter using the Washburn equation as given in Eq.(1).

$$d = \frac{-4\gamma\cos\theta}{P} \quad (1)$$

where,

d : Pore diameter, mm

γ: Surface tension, Newtons

θ: Contact angle, degrees

P : Pressure, MPa

2.5 Rapid chloride permeability test(RCPT)

Rapid chloride permeability test was used to assess the permeability of cement-free mortar comparing to that made of OPC. This test is based on the standard test method of ASTM C 1202. In this study, however, the mortar specimens were used to minimize the effect of interfacial transition zone(ITZ). A mortar cylinder, 50mm in thickness and 100mm in diameter, was connected to two chambers: one was filled with 3.0% sodium chloride and the other chamber with 0.3M sodium hydroxide to form electrodes.

3. EXPERIMENTAL RESULTS

3.1 Fundamental Properties of activated GGBS mortar

On this section the main results obtained from the experimental tests are displayed. Results on the needles penetration resistance test for setting time are shown on Fig. 1. As already mentioned, the initial set was defined as 3.43MPa and final set as 27.5MPa, and the workable period was calculated as the difference between them. Results on the workable time are presented on Fig. 2. For an appropriate usage, is advisable that for the workable period to be at least the same as for OPC mortar.

Analyzing the results, it is clear that for KOH and NaOH activated mortars the setting time reduces when the activators concentration increases. The workable period for OPC mortars was found to be around 150 minutes. For GGBS mortars activated with KOH results were found to be approximately 300, 200, 100 and 50 min for 0.5, 1.0, 2.0 and 3.0% of activator concentration respectively. For NaOH, results showed 480, 180, 80 and 50 minutes, respectively for increasing concentrations of activator. Compared to OPC, samples activated with NaOH at 1.0% showed the most similar result. Notwithstanding, activated mortar with $Ca(OH)_2$ showed different trends in initial set and final set compared to other activators. $Ca(OH)_2$ mortar samples had much longer workable period compared to OPC and the setting time was not influenced by the activator concentration, results being 350, 400, 390, 420 minutes, respectively for increasing activators concentration.

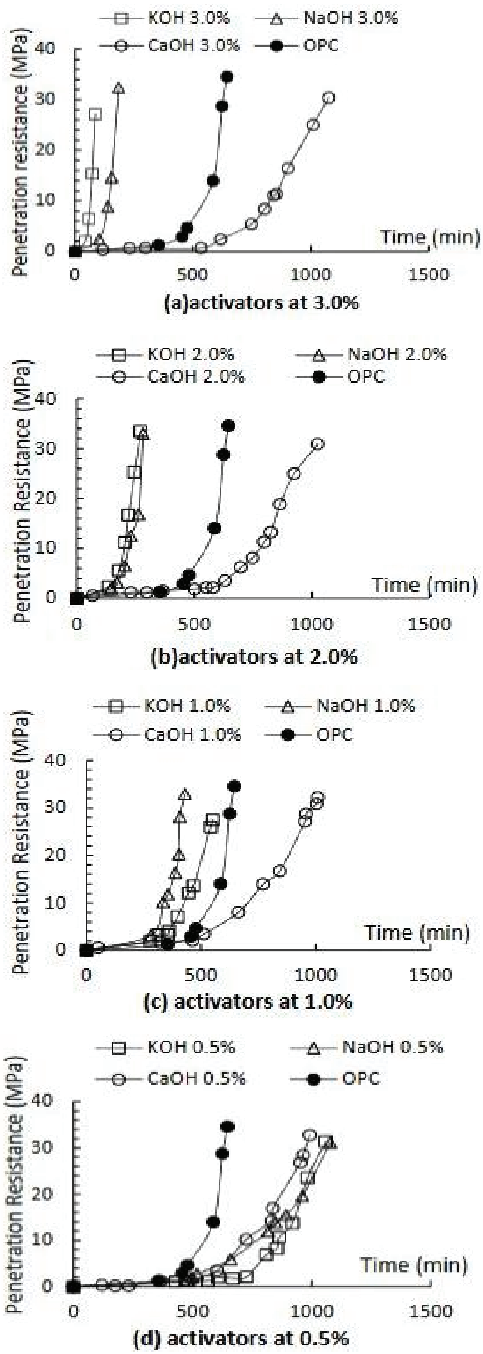

Fig. 1. Penetration Resistance of cement-free casted with (a) KOH, (b) NaOH, and (c) $Ca(OH)_2$ compare to that of OPC

Concerning compressive strength, the tests were performed for 7, 14, 28, 56, and 91 days following the recommendations provided by the Korean standards. However, as it was mentioned on the experiments section, the age of 28 days is the most important for analyzing mortar functions, differently

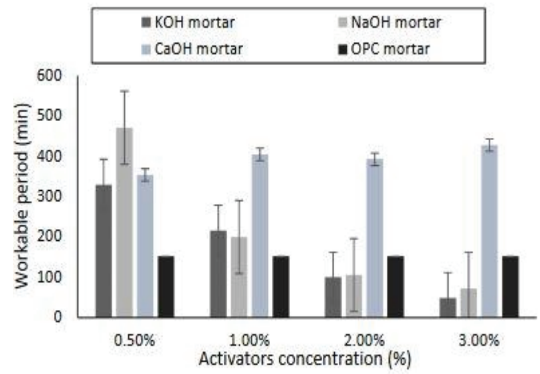

Fig. 2. Workable period of cement-free mortar mixed with KOH, NaOH, and $Ca(OH)_2$ compared to that of OPC mortar for different concentrations

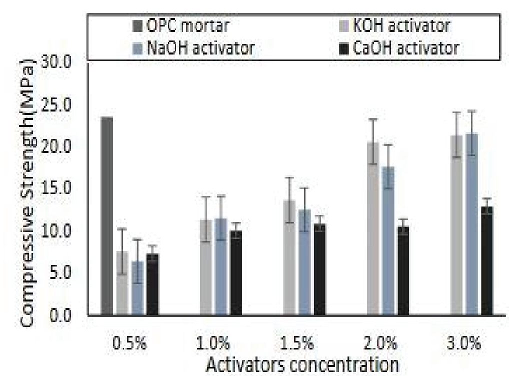

Fig. 3. Compressive strength of cement-free mortar at 28 days mixed with KOH, NaOH, and$Ca(OH)_2$ compared to that of OPC mortar at different concentrations of activators

from concrete, where the development of compressive strength shows significant importance. Therefore, this paper highlights only results for 28 days as shown in Fig. 3.

It can be seen that as the activator concentration increases, compressive strength increases at a similar proportion. For OPC mortar, the compressive strength at 28 days was found to be approximately 24.0MPa. For GGBS mortar, at 0.5% concentration of activator, results showed 7.0, 5.0 and 6.0 MPa for KOH, NaOH and CaOH, respectively, which is remarkably low. At 1.0% and 1.5% not much changed, and only a small increase was found, being the best results for KOH activated mortars, that reached 12 and 15 MPa. However, the development of compressive strength shows a consistent increase after 2.0% by weight of binder. For 2.0% results were found to be on the range of 22, 19 and 12 MPa KOH, NaOH and CaOH, respectively and 24, 25 and 15MPa ar 3.0% of activator. A possible reason to explain this increment is because the high concentrations and types of cation that could affect the hydration rate of cement-free paste. Moreover, these results are in accordance with Jimenez et al.(1999), who evaluated compressive strength of activated GGBS mortars and analyzed how the concentration, chemical nature of the activator, fineness and curing temperature affect this property. His results also indicated that the concentration and type of activator are very crucial in determining development of strength and the rate of hardening. Additionally, the mentioned author stated that for tensile strength in bending, the activator has considerable influence, but only up to 28 days, since after this period the curing temperature becomes more relevant. Another important observation concerns the fact that samples with KOH or NaOH had always better results than samples activated by $Ca(OH)_2$ that had limitations in development of compressive strength. For this latter case, mortar samples mixed at all concentration of activators had almost same strength, which was always too low compared to OPC.

On which concerns the porosity analysis and consequent permeability, MIP test results are presented in Fig. 4. It can be observed that GGBS mortars have higher cumulative pore volume than OPC, except for KOH which shows a more similar trend. For OPC and KOH the total cumulative pore volume was found to be in the range of 0.10mL/g, while for samples activate with NaOH and $Ca(OH)_2$ results pointed to 0.1207 and 0.1353 respectively. Cement-free mortar mixed with $Ca(OH)_2$ presented the highest total pore volume, however the threshold diameter of pores for alkali activated GGBS mortar mixed with KOH or NaOH was bigger than that of $Ca(OH)_2$. The critical pore size was represented to the steepest slop of the cumulative porosity curve.

Relying only on MIP results to define the durability of mortar, on which concerns permeability, could lead to significant errors, therefore results from the RCPT tests are presented on Fig. 5 to complement the analysis. It can be seen that alkali activated GGBS mortars had better performance than OPC, showing a remarkably lower permeability. Highlighting that GGBS mortar activated with $Ca(OH)_2$ had the lower permeability on the test. Therefore, it is possible to say that although the cumulative pore volume was found to be higher than for OPC, possibly the pore network of GGBS activated mortars is more complex and more connected, which reduces permeability and provide better durability.

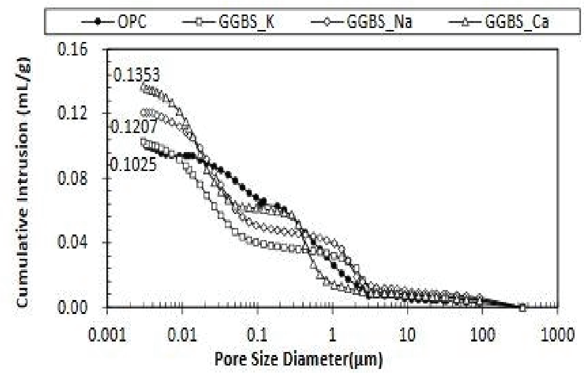

Fig. 4. Cumulative Intrusion of cement-free mortars with three different activators and OPC mortar

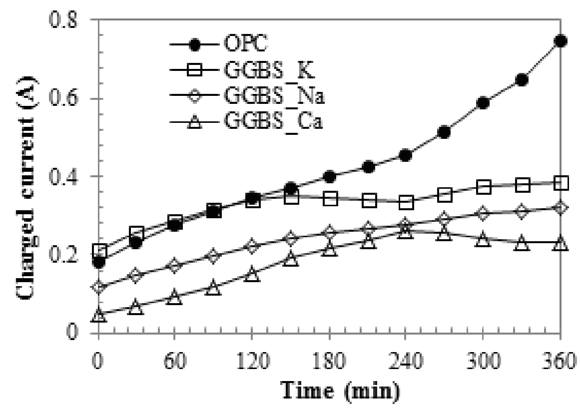

Fig. 5. Charged current with time for cement-free mortar compare to OPC mortar

3.2 Classification of samples according the results

Lastly, based on the experiment results, in order to define which usage is the most favorable for each kind of GGBS activated mortar it is necessary to briefly explain the key factors concerning each function. For laying mortar, the most important characteristics are workability, adhesion and sufficient compressive strength, especially because these characteristics in the fresh state will influence properties in the hardened state. A satisfactory state for workability is perceived when the paste adheres well to the trowel, slides easily and remains moldable for enough time to make all the alignment settings of the masonry. The intensity of hydration reactions of the paste influences on workability and also on the type of masonry to be used, because high water retention leads to increased adhesion between mortar and the brick. For coating mortar, Isaia(2013) defines it as a subsystem applied over the masonry, used for homogenizing the surface on which finishing layers will be applied, for both internal and external surfaces. In addition to the homogenization, coating mortar must protect the masonry against physical or chemical attacks from the external environment agents and contribute to thermal and acoustic isolation. The coating is divided into layers, the roughcast and plaster. The plaster is more homogeneous having pre-defined thickness, promoting good adhesion between the roughcast and painting or any other parts. Therefore, for coating mortar the most important features must be durability, followed by permeability, especially when in contact with the external environment. A less porous paste can ensure lower permeability, also contributing to the functions of isolation.

For adhesive mortar, it is used for placing ceramic pieces to the substrate with proper adhesion preventing detachment of the ceramic pieces and absorbing deformations. Since the adhesive mortar must be fully applied in the fresh state, it requires good workability, otherwise it can occur total loss of adhesion to the ceramic piece. The reduction in setting time can occur due to evaporation or by the flash hydration. Thus, the most important factor regarding this function is using a mortar that has slower hydration and good adhesion without the need of a large quantity of admixtures. About grouting mortar, it is used in joints between the ceramic pieces to allow easy replacement in case of any piece is broken and to absorb deformations due to expansion or retractions of the system at all. Therefore, this type of mortar must have resilience, adhesion and durability since cracks may appear being favorable for water percolation and consequent damage to the coated surface. Another key feature is the setting time, because after application of grouting it is necessary to do it all again for finishing. So it is better if the mortar has slower hydration and remains more time in the fresh state, to not lose adherence and to make possible a better aesthetic finishing. For structural repair, mortar can be used for cases of abrasion of the concrete cover over the reinforcement or even in situations where during construction of the building happened a mistake on vertical alignment. This solution is indicated with caution because it depends on how severe the problem is, since it is suitable only for small areas and shallow depths. This kind of mortar could be applied directly to the surface to be treated or in addition to other material that promotes better adhesion, since if there is no adhesion repair will not resist the stresses.

Therefore, according to the analysis of the results achieved experimentally and by the important characteristics highlighted above for each kind of mortar, it is possible to indicate the most suitable function of each sample, compared with OPC as it is shown in Table 2.

Table 2. Classification of samples according to usage specification

Function	Better samples according to performances
Laying mortar	➢GGBS mortar activated with $Ca(OH)_2$ for bigger areas of application where the setting time needs to be slow.
Coating mortar/plaster	➢GGBS mortar activated with $Ca(OH)_2$ because it has lower permeability granting less water percolation. ➢GGBS mortar activated with KOH, better for places that need better thermic and acoustic isolation, since these samples are less porous.
Adhesive mortar	➢GGBS mortar activated with $Ca(OH)_2$ at 2% concentration, because it has greater setting time and better durability due to its porosity characteristics.
Grouting mortar	➢GGBS mortar activated with $Ca(OH)_2$ at 2%, for the same reasons listed above for adhesive mortar.
Mortar for structural repairing	➢GGBS mortar activated with $Ca(OH)_2$ when the repair is located on the concrete cover since it is less permeable thus, more resistant to the degradable ions penetration.

4. DISCUSSIONS

Considering the costs for GGBS total replacement in mortar it goes beyond the simple economic analysis of values, because it is necessary to think about production costs and also environmental and social costs associated with the life cycle of the material. The annual consumption of concrete in the world, one of the largest employments of cementitious materials, is 19 billion tons/m(MEHTA; MONTEIRO, 2014). This high consumption of concrete leads to increased production of Portland cement, whereas Baumert, Herzog and Pershing(2005) emphasize that this material is responsible for approximately 3.8% of greenhouse gases emissions. The cement industry causes environmental impacts at every stage of the manufacturing process including emissions of dust, noise in not acceptable intensities, vibrations due to heavy machinery and blasting. Moreover, considering the current concerns about water and energy consumption worldwide, it is important to notice that the consumption of thermal energy in furnaces for OPC industries reaches 103kW/h/ton of cement produced, which a considerable high amount. Despite the claims that cement incorporates less energy than wood and steel, the energy consumption is ten times greater, which shows another huge disadvantage in the use of this material(BRONDANI, 2015).

Classifying the alkali activated GGBS mortar according to the better function implies less waste of materials, better durability and competitive advantage related to OPC, thus increasing the possibilities of gaining space in the market. Moreover by specifying the best usage of each activator it is possible to minimize the risks of application, for example the activator $Ca(OH)_2$ brings limited compressive strength and it would not be advised to use it for structural repair, meanwhile it can be satisfactory used for other functions where compressive strength is not the main concern, such as masonry mortar.

KOH is an activator that also achieved good results concerning its lower cumulative pore volume comparing to OPC, however when in comparison, it is more expensive than $Ca(OH)_2$, thus for example in the case of coating mortar, to achieve the same results it would be a cheaper option instead of KOH, using $Ca(OH)_2$ with air entraining admixture, granting still the good thermal and acoustic insulation. Therefore, a possible suggestion of further works concerns the usage of two different activators together for improving the quality of mortar, for example when the activator is $Ca(OH)_2$, it can be good for many functions but bad for developing compressive strength, so mixing KOH with it would be a way to solve this problem. Or even using waste glass as an aggregate when the activator is $Ca(OH)_2$, since if it is finely ground glass it has pozzolanic properties, low permeability and may enhance the flow properties of fresh mortar so that very high strengths could be obtained even without the use of admixture. However, it is only possible to be sure about that after realizing experiments since complex chemical reactions would be involved.

5. CONCLUSIONS

The experiments performed to analyze the fundamental properties of alkali activated GGBS mortar such as setting time, compressive strength and porosity allowed the conclusion that each activator can provide specific favorable conditions and if so, it might be more useful to classify them depending on the application. For example, in case of coating mortar, mortar samples activated with KOH are better for places that need better thermic and acoustic isolation, since these samples are less porous. However in case of bigger external areas of application where there is no necessity of acoustic isolation, mortar activated with $Ca(OH)_2$ is a better option since it has bigger workable time and can guarantee less water percolation. Thus, this paper is valuable by showing that studying the influences of such chemical activators, it is easier to provide competitive advantage to this material, adapting its usage where the best performance could be reached and also reducing material losses at the construction site.

Conflict of interest

None.

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