Ultra-High Performance Concrete with One-part Alkali-Activated Slag

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ABSTRACT

One-part (just-add-water) alkali activated binders are of interest due to their ease in practical applications, particularly in on-site works. This paper focuses on a method to develop ultra-high performance one-part alkali activated concrete using particle packing technology. Modified Andreassen particle packing model is employed to optimize the binder and aggregate content that results in a denser matrix. Two different q-parameter values are used in designing the mixes to evaluate its influence in properties like flowability and compressive strength. Lower q-value leads to higher binder content i.e., it moves towards the finer gradation of particles. Mixes with higher fines content show better workability with high flow percentages measured by the spread table (>120% flow). Variation in water-to-binder ratio (0.25 - 0.35) affects the flow and compressive strength of alkali activated concrete irrespective of q value used in the design. Compressive strengths over 120 MPa is achieved after 28-day curing. The concept of ultra-high performance concrete with particle packing technology is well established by concrete technologists. However, its application in geopolymer concrete, in specific to one-part alkali activated materials is explored for the first time in this work.

1. INTRODUCTION

Mix design plays an important role in achieving the desired fresh and hardened properties of a concrete. There are many standard mix design methods adopted for Ordinary Portland cement (OPC) concrete which have been followed for special binding systems like alkali activated binders. One such methods is particle packaking method that is used to achieve the maximum packing density of particles (Fennis and Walraven, 2012, Shi et al., 2015; Zuo et al., 2018). The main advantage of alternative binding systems is to reduce CO_2 emission of OPC which is almost 7% of world's CO_2 emissions (Barcelo et al., 2014). Alkali activated binders perform outstanding in this case by using industrial by-products and waste materials as a source (Gartner and Hirao, 2015).

Conventionally, alkali activation is performed in two-parts by using aqueous solution of alkali hydroxides and silicates to activate aluminosilicate precursors such as fly ash or slag. However, this processing technique restricts the application of this material due to the problem of handling the corrosive alkali activators. This results in the development of technique called one-part or "just-add-water" alkali-activated cements that can be used similar as OPC concrete (Luukkonen et al., 2018). Though this technique has been developed as early as 1940 (Purdon, 1940), this material is not studied extensively as that of two-part geopolymers. In this paper, an attempt is made to design an ultra-high performance of ground granulated blast furnace slag (GGBFS) based geopolymer mix with particle packing technique using modified Andreassen model. The effect of choosing different distribution modulus (Q value) and water-to-binder ratio on the fresh and hardened properties of one-part alkali-activated cements were explored.

2. MATERIALS AND METHODOLOGY

Ground granulated blast furnace slag (GGBFS was used as binder material which is obtained from Finnsementti, Finland. GGBFS was co-grinded with anhydrous sodium silicate (SiO_2/Na_2O = 0.9) in the ratio of 9:1. Fine aggregate was sieved in to two size fractions as fine sand and coarse sand which was passing and retained in 500 µm size sieve, respectively.

Mixture proportion was designed using modified Andreassen model which gives the maximum packing density from the following equation,

$$P(d) = \left(\frac{d}{d_{max}}\right)^{Q}$$

Where, P(d) is the Cumulative percent finer than d (particle diameter) and d_{max} is the maximum size of particle used in the mixture. Q is the distribution modulus, takes values of 0.25 and 0.3 in this study to know its effect on concrete properties. Commercially available software (EMMA particle analyzer) was used to arrive at the mix design as shown in Table 1.

Table 1. Mix proportion based on particle packing model.

Q value	Co-grinded slag	Fine sand	Coarse sand
0.25	1	0.8	1
0.3	0.8	1	1

Mixture distribution of the ingredients to fit the modified Andreassen model for specified Q values are shown in Figure 1. It can be noted that lower Q value shows better fitting as it means more fine particles that fills the voids formed by coarser aggregates (Kumar and Santhanam, 2003).

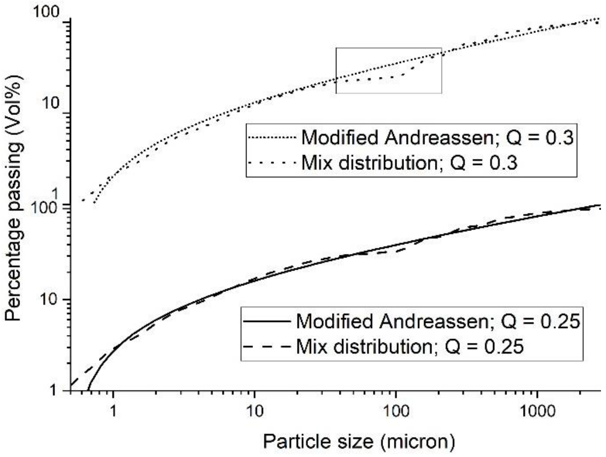

Figure 1. Mixture distribution compared with modified Andreassen model for Q values 0.3 and 0.25.

Co-grinded GGBFS, fine and coarse sand as specified in the Table 1, were mixed in Hobart mixture for 3 minutes. Calculated quantity of water (Water-binder ratio = 0.25, 0.3 and 0.35) was added to the dry mix and further mixed for 2 minutes to get a homogenous alkali activated GGBFS mortar. Flow percentage of the fresh mortar was calculated with flow table (ASTM C1437). Prismatic (40 × 40 × 160 mm) and cubic (50 mm) specimens were cast and demoulded after hardening in 24 hours. The specimens were maintained in curing chamber of 100% RH and 20°C until testing at 28th day. Eighteen prismatic beams were tested for flexural strength of different mixtures and the results are average of triplet for each mix. Three-point bending test as per ASTM C78 recommendation was followed with a deflection rate of 0.6 mm/min. The compressive strength (average of six specimens) was measured with the broken pieces of flexture testing as per ASTM C349. Cubic specimens were used to measure the porosity (average of three specimens) of the matrix as per EN 1936, with the oven drying performed at 105 ± 5˚C instead of the specified 70± 5˚C for fast drying.

3. RESULTS AND DISCUSSION

Figure 2, gives the flow percentage of geopolymer mortar with GGBFS designed with different Q values. It can be observed that mix with Q=0.25 results in higher flow percentage compared to Q=0.3, irrespective of water-binder ratio. For example, flow increased from 60% to 125% when Q value was increased from 0.3 to 0.35 at a water-binder ratio of 0.35. This can be related to the better fit to the model curve noted for lower Q value in Figure 1. Hence, optimum packing of mix ingredients plays an important role in fresh properties of mortar/concrete. Finer the ingredient, lower Q values gives good workable mix. As expected, the flow increased with increasing water content for both the Q values.

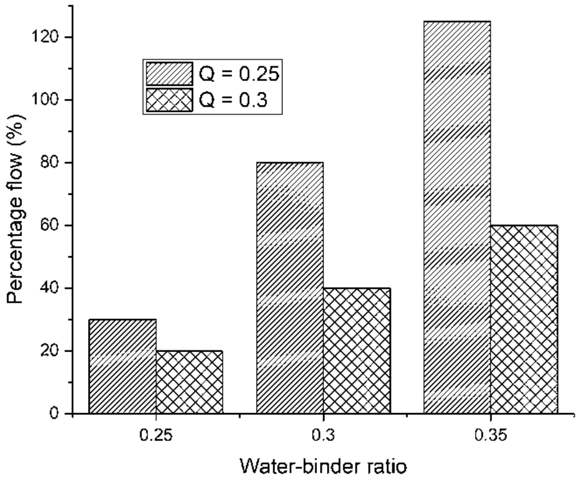

Figure 2. Effect of Q values and W/B ratio on flow percentage.

The hardened properties of the designed mixtures were analysed, and the results are shown in Figure 3 and 4. Interestingly, compressive strength increased with increasing water-binder ratio with higher Q value. As in the case of one-part geopolymer, addition of water results in four consecutive reactions as follows: (1) ion exchange, (2) hydrolysis, (3) network breakdown, and (4) release of Si and Al ions (Matalkah et al., 2017). Hence, water plays an important role in reaction initiation though further kinetics are similar to the two-part geopolymers.

Together with the packing method of mix proportion and availability of water content must have affected the release rate of Si and Al, resulting in strength increase with water-binder ratio. However, this is not the case when Q value is 0.25. Compressive strength was increasing with increasing water content and reached maximum for a water-binder (w/b) ratio of 0.3 and, reducing for further increment in water (Fig. 3). This trend is also observed with the permeable pore percentage of the mixtures as shown in Figure 4. Permeable pores are 6.5% for a w/b ratio of 0.3 and increases to 7.5% for w/b ratio of 0.35. This can be explained by the existence of an optimum water content which could result in enhanced properties of the one-part geopolymer mixtures based on the kinetics involved. For Q-value of 0.25, the optimum water content is 0.3, whereas for Q-value of 0.30 optimum water content is 0.35 or above.

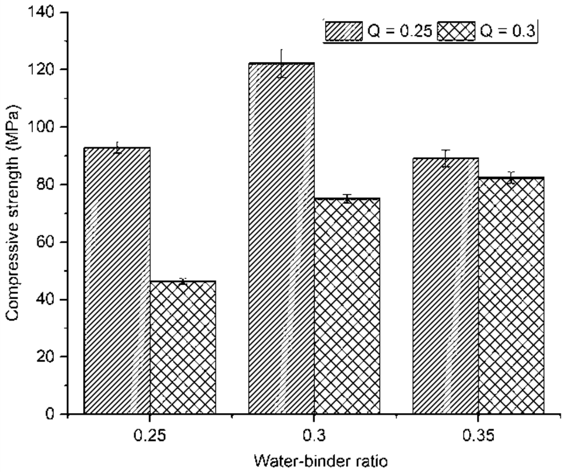

Figure 3. Effect of Q values and W/B ratio on compressive strength.

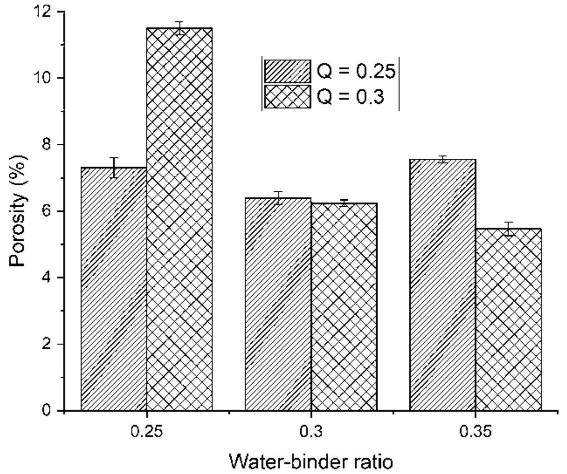

Figure 4. Effect of Q values and W/B ratio on porosity of mortar matrix.

Further analysis was made to know the reason for such a trend. Representative micrographs of one-part geopolymer made of GGBFS were captured and presented in Figure 5. In the mixtures with Q=0.25, Formation of microcracks are clearly observed in mix with w/b ratio of 0.35 whereas mix with w/b ratio of 0.3 is intact without any crack formation. It can also be noteworthy to mention that the white portions represent the unreacted GGBFSpresent in the matrix which is high in mix with w/b ratio of 0.3 (Fig. 5a) that would act as restraint in crack formation. High paste content in the other mix results in shrinkage and crack formation. Considering lower w/b ratio of 0.25, the lower compressive strength can be related to the insufficient water content for the dissolution of solid alkali sources to initiate the activation of alumino-silicate precursors.

4. CONCLUSIONS

The following conclusions are drawn based on the experiments conducted on particle packing technique of mix design in one-part alkali activated GGBFS mortar:

Workability of the mix depends on the efficient particle packing and the best fit with the model. Q value of 0.25 was superior to 0.30 in terms of fresh state flow properties.

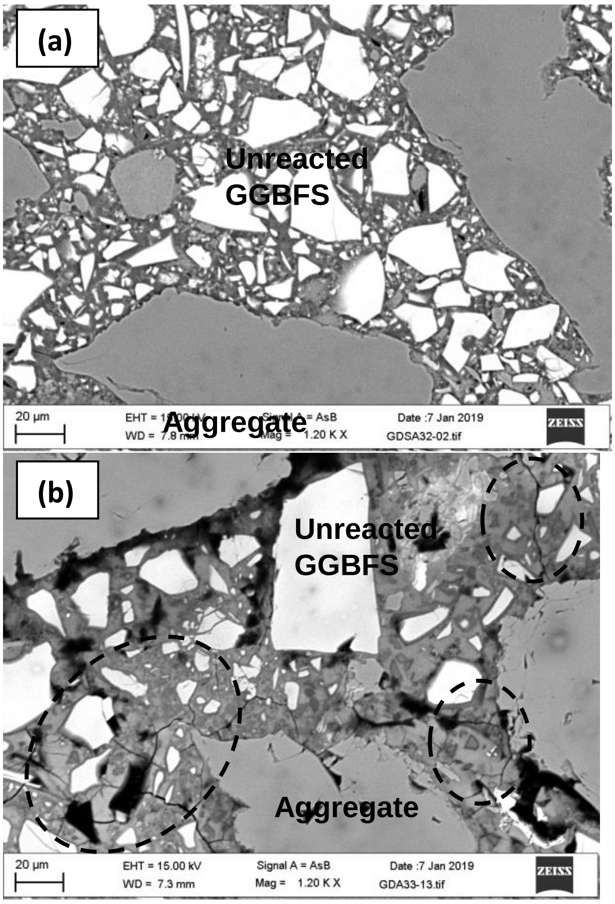

Figure 5. Representative microstructure of GGBFS-geopolymer mortar with Q value 0.25 and water-binder ratio a) 0.3 and b) 0.35.

Mechanical properties and permeable porosity depend on the water-binder ratio, which in turn depends on the mixture proportioning and Q value of the mix.

At lower w/b ratio, compressive strength is reduced. This is presumably due to insufficient water provided for the dissolution and activation of the GGBFS.

The optimum water content varies with the amount and type of mix ingredients used, and the Q value chosen. For the chosen mix design, the optimum w/b ratio was found to be 0.3 resulting in effective particle packing, lowest permeable pore percentage (6.5%) and highest compressive strength (122 MPa) for the Q value of 0.25.

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