Construction and Building Materials 58 (2014) 225–233

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Combined effect of fine fly ash and packing density on the properties of high performance concrete: An experimental approach

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HIGHLIGHTS

- HPC with superior properties has been optimized using 312 kg/m^3 binder.
- Fine FA is more effective than normal FA on improving concrete properties.
- Total porosity is reduced to 3% by combination of fine FA and SF.
- The optimized HPC has a chloride diffusion coefficient of 1.4×10^{-13} m^2/s.

ARTICLE INFO

Article history:
Received 16 October 2013
Received in revised form 5 February 2014
Accepted 8 February 2014
Available online 13 March 2014

Keywords:
Packing density
Ideal Fuller curve
Fine fly ash
Porosity
Durability

ABSTRACT

High performance concrete often contains large amount of cement which makes ecological, economical and technical problems. This study provides a new approach to optimize high performance concrete with low cementitious materials content. The ideal grading curve according to Fuller has been used in concrete mix design to ensure high packing density of concrete mixtures and to reduce the required binder content. Several systems comprising various pozzolanic materials (silica fume, fly ash and fine fly ash) have been prepared and tested. The role of fine fly ash on concrete performance has been estimated by measuring the concrete mechanical properties, porosity and durability. The mechanical properties were assessed from compressive strength and modulus of elasticity, whilst the durability characteristics were investigated in terms of water permeability, water absorption and chloride diffusion. The results showed that fine fly ash performed better than normal fly ash for the strength development and durability aspects. The ternary system containing slag cement, fine fly ash and silica fume with low w/b ratio performed the best amongst all the systems regarding concrete mechanical properties and durability. Combination of fine fly ash and silica fume with OPC or with slag cement resulted in a significant reduction in concrete porosity. All mixes containing fine fly ash exhibited high performance concrete with excellent durability properties.

1. Introduction

Nowadays, progress in science and technology in the field of construction industries and usage of new materials have resulted in the use of reinforced concrete in special structures such as sewage systems, nuclear power containments, cooling towers of power plants, high way bridges and tunnels. In such aggressive environments, high durability, stability and resistance to chemical attack are of more concern. High performance concrete (HPC) provides an attractive option for such conditions. According to Mehta and Monteiro [1], three main characteristics make the concrete with high performance: high workability, high strength and high durability. Because of the various requirements including workability, durability, strength and dimensional stability, the mix design of HPC is a challenging task. Unlike normal concrete, it is no longer sufficient to base the mix composition on the principle of compressive strength and w/c ratio relationship. HPC is produced using carefully selected ingredients and low water/binder (w/b) ratio. In addition, it requires high amount of cementitious materials (400–550 kg/m^3) and also high dosage of superplasticizer [2]. However, the use of high amount of cement can lead to environmental, economic and technical problems. For example, using high cement content increases the hydration heat and shrinkage which are critical issues for concrete [3]. To cope with these problems,

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http://dx.doi.org/10.1016/j.conbuildmat.2014.02.024
0950-0618/

more optimization is needed to minimize the cement content in order to reduce the ecological and economic impact of HPC. One possibility of optimizing the HPC mixture is the selection of concrete constituents in such a way that the packing density of the whole granulometric assemblage is maximized. Basically, increasing the packing density of aggregate would decrease the volume of paste needed to fill up the voids and increase the amount of additional paste that could be utilized to improve the workability. Additionally, the concrete will have less durability problems such as permeability, shrinkage, and thermal degradation.

2. Particle packing optimization

The packing density can be defined as the ratio of volume fraction occupied by the solids to the volume of the surrounding container. It is a matter of interest in many fields of material science such as packed beds, ceramics, asphalts and concrete [4]. The optimum packing density of the system could be attained only if spheres with smaller sizes are added to the assemblage. The small size spheres can fill the voids between the large spheres, and thereby the packing density is significantly increased. In 1961, McGeary reported that it is possible to achieve a packing density of 95.1 using four sizes of spheres with diameter ratios of 1, 7, 38 and 316 with fraction volumes of 6.1%, 10.2%, 23% and 60.7% respectively. However, the maximum density of infinite differences in sizes can be attained is 97.5% [5]. For concrete, the situation is more complex since the system is composed of various particle sizes with different shapes and sizes. Effective packing can be attained by selecting proper proportions and sizes of small particles to fill in the voids between the bigger particles. The important effects of aggregate grading on the properties of concrete have been emphasized in very early reports [6]. In 1892, Feret concluded that the maximum strength can be attained when the voids in the mixture is minimum [7]. Fuller reported that the best grading curve of aggregate to get the maximum density is a parabolic shape [8]. Both Feret and Fuller confirmed that concrete properties can be significantly improved by using continuous grading [7]. In 1923, Talbot developed the well-known equation [9]:

$$P = (d/D)^q \tag{1}$$

where P is the total percent passing through a sieve, d is the diameter of the current sieve, D is the maximum aggregate size and q is the gradation ratio. The maximum packing density can be achieved when $q = 0.5$, which is close to the Fuller curve [10,11], but the resulting concrete is harsh and unsuitable. In 1930, Andreasen tried to improve the Fuller curve. He suggested using the exponent q in the range of 0.33–0.5, because fine particles are not able to pack similar to bigger particles [12].

3. The work of Fuller and Thompson

Fuller and Thompson studied the grading analysis for a wide variety of aggregate types and mixtures to achieve the maximum packing density. They found that the best density of aggregate can be attained when the particle size distribution of aggregate is continuously graded and the grading curve takes a parabolic shape (Fig. 1). This curve is known as Fuller parabola and can be applied for calculating the optimum grading of aggregate only (not for a mixture of aggregate and binder) as Fuller mentioned later [8]. This is because the mixture of aggregate which gives the maximum density in the dry state does not necessarily achieve the greatest density when combined with cement and water. The very low void content between the aggregate prevent the cement and water to fit in perfectly [8]. In addition, Fuller parabola leads to low powder content, whereas, more fines are needed to maintain good cohesion and to prevent segregation.

In 1903, Fuller and Thompson began an intensive work to achieve the greatest packing density for mixtures of aggregate and fine materials with maximum size of 2.25 inch. The ideal grading curve has been obtained by trial mixes without referring to mathematical basis. To get this curve, at least 7% of the solid materials should be finer than the No. 200 sieve. It composed basically of an ellipse at the lower part and merging into a straight line tangent to the elliptical part [11]. The ellipse begins from 0.0029 inch (sieve No. 200) and runs to a value of x equals to one-tenth the maximum grain size (Fig. 1). At this point, the straight line begins and continues to $y = 100\%$ and $x = D$ (where D is the maximum grain size). After finding the ideal curve, equation was fitted to this curve. The equation covering this ideal grading curve is divided into two parts:

For the elliptical part:

$$\frac{(y-7)^2}{b^2} + \frac{(x-a)^2}{a^2} = 1 \tag{2}$$

For the straight line part:

$$y = \frac{100 - y_1}{D - x_1}(x_0 - x_1) + y_1 \tag{3}$$

where a and b are the axis of the ellipse and their values depend mainly on the shape of the particles and the maximum aggregate size [11], $x_0 = D/10$ to D, $y_1 = y$ of the ellipse at $D/10$ and $x_1 = D/10$ [13].

In 1992, Puntke reviewed Fuller work and redraw the ideal curve in a semi-logarithmic scale for the sake of simplicity (Fig. 2) [13]. This curve has been used for designing concrete mixes for several applications, particularly those, which need high density and high resistance to acid attack. For example, in 2000, the highest cooling tower in the world (200 m, Niederaußem, Germany) has been constructed of acid resistant concrete. The used concrete has been designed on the basis of the ideal Fuller curve. By applying this concrete in the cooling tower, the tank did not need any internal protective layer (as normal) because the used concrete has high density as well as high resistance to acid attack [14,15].

4. Mix design

In this investigation, the concrete mixture proportioning is based on the granular optimization of all concrete constituents according to the ideal Fuller curve. The maximum grain size of coarse aggregate was 16 mm. For this size and according to the ideal Fuller curve (Fig. 2), the required aggregate volume ($d > 125$ μm) is 85.13%, while the binder volume ($d < 125$ μm) is 14.87%. According to this calculation, the required amount of cementitious materials and aggregates are 312 and 1984 kg/m^3 respectively. On the other hand, to obtain a good size distribution, the skeleton of aggregate size fractions should be viewed as a whole rather than two separate entities; coarse and fine aggregate. Aggregate as they come from the quarry do not normally have size distributions that fit the dense packing curve as can be seen in Fig. 2. There are some deviations between the non-optimized mixture and the ideal Fuller curve. The mixture has more materials in the range of 0.5–2 mm. Therefore, sieve analysis of aggregate is necessary to be done and the required amount of each size is taken. On the contrary, the mixture has low fine materials in the size range 0.063–0.25 mm. Thus, quartz sand and quartz powder are added to fill this gap and to densify the matrix.