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Effect of paste amount on the properties of self-consolidating concrete containing fly ash and slag

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HIGHLIGHTS

- Effect of paste amount on the properties of concrete.
- Densified mixture design algorithm for mix proportion.
- The proper paste amount the better the workability and the less the workability loss.
- The amount of cement paste and water should be minimized as low as possible for good quality feature.

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ABSTRACT

The objective of this paper is to compare the performance of concrete containing fly ash and slag under different water-to-cementitious materials ratios and different cement paste content. The densified mixture design algorithm (DMDA) was applied in the concrete mix design. Concretes designed by DMDA with excellent flow-ability and without bleeding and segregation were obtained. The proper paste amount the better the workability and the less the workability loss. On the basis of sufficient paste amount condition, the study discovers that the less the cement paste amount as well as the denser the blended aggregate, the lower the early-age compressive strength will be, on the contrary, the higher the long-term compressive strength becomes. To design of good quality concrete, the amount of cement paste and water should be minimized as low as possible to obtain the high ultrasonic pulse velocity.

1. Introduction

Nowadays, five requirements including workability, safety, durability, economy and ecology, should be put together for success in concrete industry. First of all, using too much water results in higher possibility of bleeding and segregation, which is not favorable for strength development, interface strength, volumetric stability [1] and durability [2]. To attain better workability, the addition of superplasticizer (SP) is one of the strategies enabling the use of less water [3]. Replacing cement partially with pozzolanic materials can also lower the hydration rate. The amount of paste needed can be minimized by controlling the gradation of aggregates [4,5]. Secondly, the safety of concrete depends on the water-to-cementitious materials (w/cm) ratio (cementitious materials including cement and pozzolans) for medium and long-term strength and the water-to-solid (*w*/*s*) ratio for its long-term properties. Thirdly, long-term performance is expected to be better because of a pozzolanic reaction that converts soluble alkali into more stable C–S–H gel [6,7]. Durability is a very important property of concrete and many studies have found that the use of an excessive amount of cement, and hence water, will result in high permeability which will have a negative effect on the quality [3,4,8]. Calcium hydroxide from the cement hydration may cause sulfate attack, leaching and precipitation, which is harmful to the concrete. A simple way to increase durability is to reduce the water content and cement content. In addition, decreasing the amount of cement used will reduce hydration heat and volume change [9]. Fourthly, as far as cement paste is concerned, the content of expensive cement needed can be reduced. The life of concrete may be prolonged because of improved durability. Another mean to achieve economy is to employ the cheap indigenous resources and recycling materials, such as fly ash and slag. In addition, concrete with good workability may make construction work easier, thereby reducing the labor and cost involved. Last but not least,

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using less cement reduces energy consumption and CO_2 emissions during the production process. Taken together, it is clear that the performance of concrete relies heavily on the appropriate amount of paste used. To achieve better performance, chemical admixture and pozzolanic materials as well as the low water content and low amount of cement paste should be used. This view point seems to be conflicted with traditional viewpoint that concrete having high strength and better durability require low water-to-cement ratio and low amount of water in its mix design. Therefore, the behavior of paste amount containing pozzolanic materials should be fully understood.

The role of paste amount on the properties of concrete has long been a matter of interest of researchers. Most of investigators have reported that the higher the volume of the paste, the lower the strength of comparable concretes of identical water-to-cement ratio (w/c) [10–13]. The maximum paste thickness (MPT) concept [11] which was defined as the maximum distance between adjacent coarse aggregates has been used to explain the reasons for this effect. When the amount of the paste is higher, the amount of the aggregates is less. This leads to the higher MPT and hence the matrix strength becomes lower. Recently, the effect of paste volume and water content on the strength and water absorption of concrete without mineral admixtures having the same effective water-to-cement ratio (W_{ef}/C) ratio has been researched by Kolias and Georgiou [10]. In 2007, Rozière et al. [13] have studied the influence of paste volume on shrinkage cracking and fracture properties of self-compacting concrete having additive of limestone filler. Leemann et al. [14] have researched on the influence of paste volume and binder type on the stress–strain-behavior of self-consolidating concrete (SCC) and conventionally vibrated concrete (CVC) with identical aggregate type and size distribution and identical w/c but with a difference in paste volume of about 150 l/m^3 and in aggregate content of about 400 kg/m^3. They have concluded that compressive strength of CVC was higher due to the higher amount of cement paste and the lower amount of aggregate in the SCC mixtures, even at 2-day age. However, three above studies just have recorded the effect until the age of 28 days.

It is deemed by the classical concrete mixture proportion that aggregates are the main skeleton of concrete, and the paste requirement for workable concrete is determined by the gradation of aggregate. In practice, it is found that the maximum packing density of aggregate is advantageous for making concrete regarding to workability, necessary strength, stiffness, creep, shrinkage, permeability, and durability. The idea of packing density gradually substitutes for the rich mixture of a large amount of cement and has a greater importance for making flowing high performance concrete (HPC) or SCC than others. Theoretically, under maximum packing density of aggregate, concrete requires only very little cement paste to glue aggregate together for better strength. Therefore, an assessment of the influence of paste amount on the properties of concrete under the maximum packing density of aggregate concept is needed in order to gain a better understanding of this influence.

The pozzolanic materials play important roles in the properties of concrete from micro structure, chemical and physical point of view. Fly ash has been widely used in concrete industry as important supplementary cementitious materials and is now an important ingredient of HPC and SCC because of the availability of fly ash. Fly ash with spherical shape improves the workability of fresh concrete due to the ball bearing effect at low addition of about 5–20% and affects the volume stability of hardened concrete. A large amount of fly ash is not helpful in workability without the addition of other chemical admixture due to its low density, but if at proper proportions it will be quite helpful to reduce the problems of bleeding and segregation. Also due to its spherical ball in shape, fly ash buoys the aggregate, and therefore minimizes the settlement rate of aggregate. Concrete with high amount of fly ash content requires longer periods of time to develop strength due to the slow hydration reaction of fly ash. Only 20% of fly ash reacts after 90 days [6]. The early-age strength (≦14 days) of the fly ash concrete mixtures with 40% of fly ash or higher were less than the control mixture. However, at later age (≧56 days), fly ash concrete mixtures with 60% of fly ash and less have similar or higher compressive strength than the control mixture [15]. The chemical composition of slag consists mainly of calcium aluminosilicate and iron oxide. Therefore, it can be called slag cement. Slag will act hydraulically in concrete as a partial replacement for Portland cement. Similar to fly ash, due to the low hydration reaction high slag cement concrete has low strength at early ages [6].

The aim of this research is therefore to reach a clearer understanding of the effect of paste volume containing fly ash and slag in the strength and quality of concrete, from which the densified mixture design algorithm (DMDA) [16–18] was applied for concrete mix-design.

2. Materials and experimental methods

2.1. Materials

Type I Portland cement, Class F fly ash (FA), and ground granulated blast-furnace slag (GGBS) conforming to ASTM C150, ASTM C618 and ASTM 989, respectively, were used in this study. The physical properties and chemical compositions of these materials are given in Table 1. Crushed coarse aggregate (D_{max} 12.7 mm, density 2.64, water absorption capacity 0.91% and unit weight 1507 kg/m^3) and natural sand (modulus of fineness 2.95, density 2.64, absorption capacity 1.2% and unit weight 1649 kg/m^3) were provided from local quarries. The mixing water was local tap water. Type-G superplasticizer, having 43% solid content with specific gravity of 1.18, was used to achieve the desired workability for all concrete mixtures.

2.2. Mixture proportions

The DMDA method is developed from the hypothesis that the physical properties will be optimum when the physical density is high. The major difference from the other mixture design algorithms is that instead of partial replacement of cement, DMDA incorporating fly ash is used to fill the void of aggregates and hence increase the density of the aggregate system. The purpose of such action is to reduce the cement paste content for design properties such as workability, strength, and workability. As a result, besides physical acting as filler, fly ash acts chemically as a pozzolanic material.

The maximum weight ratio α_{max} of blended sand and fly ash can be expressed as the Eq. (1):

$$\alpha_{max} = \max\ \alpha = \frac{w_F}{w_F + w_S} \quad (1)$$

where w_F and w_S is the weight of fly ash and sand, kg/m^3, respectively.

Then, the blended fly ash and sand mixture at a fixed ratio of α_{max} is used to fill the void within coarse aggregates. Using a similar process, the maximum dry, loose density of blended aggregates can be obtained from the plot of blended coarse aggregate and fly ash/sand mixture. The weight ratio β_{max} at the maximum dry, loose density can be expressed as the Eq. (2):

$$\beta_{max} = \max\ \beta = \frac{w_F + w_S}{w_F + w_S + w_{ca}} \quad (2)$$

Table 1
Chemical analysis and physical properties of cement and pozzolans.

Items	Cement	Fly ash	Slag
Fineness (cm^2/g)	3310	3110	4350
Specific gravity	3.15	2.18	2.88
Chemical composition (wt.%)			
SiO_2	22.01	51.23	34.86
Al_2O_3	5.57	24.31	13.52
Fe_2O_3	3.44	6.14	0.52
CaO	62.80	6.28	41.77
MgO	2.59	1.61	7.18
SO_3	2.08	0.61	1.74
Free CaO	1.05	–	–
$TiO_2 + Na_2O + K_2O + V_2O_5$	1.75	–	–