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The mix design for self-compacting high performance concrete containing various mineral admixtures

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ABSTRACT

This paper is an effort towards presenting a new mix design method for self-compacting high performance concrete (SCHPC) containing various mineral admixtures (MA). In the proposed method, the constituent materials were calculated by using the absolute volume method. The packing theory of Funk and Dinger with the exponent $q = 0.25$ was adopted to determine the grading of aggregate. The primary paste volume for filling capacity was computed from the void content of compacted aggregate. The superplasticizer dosage for the concrete was set on the basis of the superplasticizer saturation dosage of the corresponding mortar. Efficiency factors were used to express the effect of MAs on compressive strength of concrete. The results show that the method was adequate to proportion SCHPC mixtures containing ternary binders, i.e. cement and two different MAs (rice husk ash (RHA), silica fume, fly ash, and lime stone powder), satisfying the self-compactability requirements and compressive strength class in the range of C60/75–C90/105. With 5–20 wt.% cement replacement, RHA was very effective in improving compressive strength of SCHPC. The efficiency factor for RHA, i.e., 2.7–1.8, which is the first time applied, is only marginally lower as compared to that of silica fume.

1. Introduction

Self-compacting concrete is a concrete that can flow and consolidate under its own weight, pass through the spaces between the reinforcement bars to completely fill the formwork, and simultaneously maintain its stable composition [3–5]. Self-compacting high performance concrete (SCHPC) is defined as a new generation of concretes on the basis of the concepts of self-compacting concrete (SCC) and of high performance concrete (HPC). A method for proportioning SCHPC aims at fulfilling the self-compactability requirements of SCC (filling ability, passing ability, and segregation resistance), as presented in Table 1, and of high compressive strength and good durability of HPC [6]. To realize this goal, a high volume of Portland cement, a very high dosage of chemical admixtures, i.e. super plasticizer (SP) and viscosity modifying admixtures, and reactive mineral admixtures (MA), e.g. silica fume (SF), are used [5–7]. Hence, high costs and environmental impact constitute the main disadvantage of SCHPC. The performance of SCHPC is highly improved by using SF however it is expensive due to the limited availability especially in developing countries. Rice husk ash (RHA), with its high amorphous silica content, is a very good replacement for SF with regards to compressive strength and durability of concrete [6,8–12]. The reactive RHA is the residue of under proper conditions completely incinerated rice husk. Rice husk, the outer covering of a rice kernel, is an agricultural waste from the milling process of paddy. Rice husk is abundant in many rice cultivating countries, e.g. Vietnam, India and China. Normally, rice husk from paddy rice mills is disposed directly into the environment or sometimes is dumped or burnt in open piles on the fields. This results in serious environmental pollution, especially when it is disintegrated in wet conditions. Substitution of less-expensive RHA for SF as a partial cement replacement, not only improves the sustainability of SCHPC, but also reduces environmental pollution from the disposal of rice husk.

It is well known that mix design is of major importance for the concrete production process. The mix design can be understood as combining optimum proportions of the constituent materials to fulfill the requirements of fresh and hardened concrete for a particular application [13]. Generally, in the mix proportioning of

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Nomenclature

A	the designed air content (vol.%)
A_i	the content of the air-dry aggregate *i* (kg/m^3)
a_i	the ratio of aggregate *i* to aggregate blend (wt.%)
AB	the content of aggregate blend (kg/m^3)
B	the binder content (cement plus MA) (kg/m^3)
C'	the cement content in the MA-blended concrete (kg/m^3)
$D_{\min}$, $D_{\max}$	the minimum and maximum particle sizes in the aggregate blend (mm)
$f_{c,\text{cube}}$	the characteristic minimum cube compressive strength (MPa)
$f_{c,\text{dry,cube}}$	the average cube compressive strength cured in dry conditions (MPa)
k_i	the efficiency factor of MA$_\text{i}$
M_{A_i}	the moisture content of aggregate *i* (wt.%)
n	the number of MA used
$P(D)$	the weight percentage of aggregate passing the sieve with size *D* (wt.%)
P_{MA_i}	the content of MA$_\text{i}$ (kg/m^3)
p_i	the percentage of cement replaced by MA$_\text{i}$ (wt.%)
$R_{S,A}$	the coefficient related to the shape (*S*) and the angularity (*A*) of aggregate in the range of 1–5 [1]
SP	the dosage of SP (wt.%)
S_{sp}	the solid content of SP (wt.%)
V_{AB}	the absolute volume of the aggregate blend (m^3)
V_{A_i}	the absolute volume of aggregate *i* (m^3)
V_{exp}	the excess paste volume (vol.%)
V_p	the primary paste volume required for filling ability (vol.%)
V_{void}	the void volume of the compacted aggregate blend in concrete (vol.%)
$Voids$	the void content in compacted aggregate blend (vol.%)
WA_{A_i}	the water absorption of aggregate *i* (wt.%)
W_{ad}	the adjusted water content (kg/m^3)
γ_{AB}	the bulk density of dry aggregate blend (kg/m^3)
Δf_c	the allowance for compressive strength (6–12 MPa) regulated in DIN EN 206-1 [2]
ρ_{A_i}	the density of aggregate *i* (kg/m^3)
ρ_{AB}	the density of dry aggregate blend (kg/m^3)
ρ_c	the density of cement (kg/m^3)
ρ_{MA_i}	the density of MA$_\text{i}$ (kg/m^3)

ordinary concrete, the required compressive strength is the prime criterion. For SCHPC, however, self-compactability, compressive strength and durability are equally taken into account in proportioning mixtures [6]. Regarding the properties of SCC/SCHPC, there exist two main mix design approaches to proportioning mixtures. One approach emphasizes on self-compactability, and ignores or does not give equal importance to compressive strength and durability as presented in [1,4,14,15]. This approach does not render properly controlling the compressive strength, nor reaching high compressive strength levels due to the high *W*/*B* ratio determined from the water demand of the binder. The other approach considers self-compactability as well as compressive strength as the targets of mix design for SCC/SCHPC. Compressive strength of SCC/SCHPC designed by these methods ranges mostly from 30 to 90 MPa [16–18]. This kind of method does not take into consideration the effect of MAs on self-compactability and compressive strength of SCC/SCHPC. Regarding the utilization of MAs in SCC/SCHPC, several individual MAs such as FA, RHA, SF, and ground granulated blast-furnace slag (GGBFS), are taken into consideration in the mix design to satisfy adequate self-compactability and required compressive strength [6,19–22]. Each MA has its own advantages and disadvantages. Combination of various MAs can exploit their advantages and increase the cement replacement level. In order to take into account the effect of MAs on the mechanical properties of concrete, the concept of "efficiency factor" has been developed. The efficiency factor is empirically determined for the given content of materials and the exposure conditions [23–25]. The efficiency of RHA and other MAs will be presented in the next section. The efforts to relate the efficiency factor of MAs and compressive strength in mix-design for SCC/SCHPC are scarce in the literature, especially when more than one MA is used as cement replacement to achieve a particular high compressive strength exceeding 90 MPa.

In this study, a simple mix design method for SCHPC was developed on the basis of the cementitious efficiency of mineral admixtures and of the requirements for ordinary concrete proportions laid down in DIN EN 206-1 [2] and DIN EN 1045-2 [26]. The proposed method was applied to design mixture proportions of SCHPC containing ternary binders, i.e. cement and two different MAs, i.e. RHA, SF, FA, and LSP, at various low *W*/*B* ratios.

2. Cementitious efficiency of RHA and other mineral admixtures

All kinds of MAs, i.e. nearly inert, pozzolanic and latent hydraulic MAs, have been used to produce SCHPC. Where LSP is nearly inert or low reactive. SF, RHA, metakaolin, and low calcium class F-FA (according to ASTM: C618) are pozzolanic. And ground granulated blast-furnace slag and high calcium class C-FA (according to ASTM: C618) are both latent hydraulic and pozzolanic MAs [6,8,13]. Each type of MA exerts different effects on properties of both fresh and hardened concrete depending on its characteristic and replacement levels. In terms of compressive strength, the effect of MA can be expressed as an efficiency factor (*k*-value). The efficiency factor is defined as the portion of MA, which can be considered as equivalent to Portland cement in a MA-containing concrete. A *k*-value of a MA equal to 1 indicates that the MA is equivalent to cement. On the contrary, a *k*-value less than 1 implies that the MA underscores cement as to its effect on compressive strength. The content of a MA can be multiplied by the *k*-value to convert to the equivalent cement content [23].

Recently, the efficiency factors for compressive strength of calcined kaolin and SF have been determined by the procedure proposed by Wong and Abdul Razak [25]. The *k*-value of a MA is obtained from the ratio of compressive strength of the MA-blended mixture to the control mixture (containing 100% OPC). It is generally concluded that the *k* factors increase with age but decrease with higher pozzolanic content. It was also observed that changes in *W*/*C* ratio from 0.33 to 0.27 did not significantly affect the resultant efficiency factors. The fundamental principle of Abram's rule is applied in the method. The compressive strength of the MA-blended mixture is inversely proportional to the water to equivalent cement content ratio (W/C_{eq}), where the equivalent cement content is $C' + kP_{MA}$. The compressive strength of Portland cement concrete, f_c, can be expressed by:

$$f_c = K_1\left(\frac{1}{W/C}\right) \tag{1}$$

The compressive strength of concrete containing a MA, f_{MA}, can in analogy with Eq. (1) be expressed by:

$$f_{MA} = K_2\left(\frac{1}{W/(C' + kP_{MA})}\right) \tag{2}$$