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A Simple Mix Proportion Design Method Based on Frost Durability for Recycled High Performance Concrete Using Fully Coarse Recycled Aggregate

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Abstract: Durability design of recycled high performance concrete (RHPC) is fundamental for improving the use rate and level of concrete waste as coarse recycled aggregate (CRA). We discussed a frost-durability-based mix proportion design method for RHPC using 100 % CRA and natural sand. Five groups of RHPC mixes with five strength grades (40, 50, 60, 70 and 80 MPa) were produced using CRA with four quality classes, and their workability, 28 d compressive strengths and frost resistances (measured by the compressive strength loss ratio and the relative dynamic modulus of elasticity) were tested. Relationships between the 28 d compressive strength, the frost resistance and the CRA quality characteristic parameter, water absorption, were then developed. The criterion of a CRA maximum water absorption limit value for RHPC was suggested, independent of its source and quality class. The results show that all RHPC mixes achieve the expected target workability, strength, and frost durability. The research results demonstrate that the application of the proposed method does not require trial testing prior to use.

Key words: recycled high performance concrete; mix proportion design; frost durability; compressive strength; water absorption

1 Introduction

It is well established that the application of concrete waste as a replacement for natural coarse and fine aggregates for structural concrete has many advantages, such as efficiently removing and disposing concrete wastes, reducing the load on landfills, and compensating for the growing shortage of natural aggregates. Over the past few decades, several studies on the structural behaviour of recycled aggregate concrete (RAC) composed of aggregate from concrete waste have been conducted, and the findings[1-3] have proved the feasibility of using concrete waste for structural concretes. However, RAC often has lower strength and durability performance compared to natural aggregate concrete due to the poorer quality of recycled aggregate resulting from mortar attached to its surface. Consequently, a RAC geared towards high performance concrete (HPC) is required, which emphasizes high workability, high strength and high durability. However, a durability-performance-based method for designing the mix proportion of HPC has yet to be established with a full consideration of the quality of recycled aggregate. Currently, there is no comprehensive design method for recycled high performance concrete (RHPC) that applies to a wide range of strength and durability levels and different types of recycled concrete aggregates. In summary, current design procedures are only valid for a limited range of compositions, so establishing a widely applicable method is of great value.

In this work, an easy and effective method for designing RHPC with fully coarse recycled aggregate (CRA) based on frost durability is presented. This method can be extended to any type of CRA and is sufficiently simple to be easily implemented into practice. Our method considers water absorption as a quality characteristic parameter of CRA and is based on a relationship between water absorption and frost

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durability, which was evaluated using the compressive strength loss ratio and the relative dynamic elastic modulus loss ratio. Contrary to most current methods, the suggested mix design procedure is based on non-empirical expressions and can simultaneously address the requirements of workability, strength and frost durability of RHPC. Finally, five examples are presented to demonstrate the wide applicability of our approach.

2 Experimental

2.1 Materials

Seven commercial CRAs with nominal sizes of 5-20 mm were used to represent the range of types of CRA, including varied sources and quality classes. Their sources, physical properties and quality classes are indicated in Table 1. The CRA source, concrete waste, is divided into two types: a single type with one mix proportion and a mixed type with two or more mix proportions, identified as 1 and 2 in Table 1, respectively. The CRA quality class was evaluated in accordance with China Standards GB/T 25177-2010, for which there are three classes: Class Ⅰ, Class Ⅱ and Class Ⅲ. Those CRAs with a quality class below Class Ⅲ (marked as "Below Standard" in Table 1) do not apply to structural concrete. In all, a total of four quality classes were considered, covering all possible quality levels of CRA.

Four binders were used for the RHPC preparation, ordinary Portland Cement 52.5 with a density of 3.12 g/cm^3 and a Blaine specific surface area of 336 m^2/kg, finely ground slag with a specific surface area of 463 m^2/kg, class Ⅱ fly ash with a specific surface area of 460 m^2/kg, and silica fume with a specific surface area of 2473 m^2/kg. Natural sand (particle density ~ 2 680 kg/m^3) with a nominal size of 0.36 - 4.75 mm was selected as the fine natural aggregate. Polycarboxylate superplasticizer (JK-PCA, made in the Changzhou Institute of Building Science) and an air-entraining agent (AOS) were used to increase the workability and durability of the RHPC.

2.2 Concrete mixing, specimen preparation and tests

Five groups of RHPC mixes with strength grades of 40, 50, 60, 70 and 80 MPa were designed to characterize the relationship between RHPC properties (workability, strength and frost resistance) and CRA quality. For each group, four quality classes of CRAs were used.

The concretes were produced in a forced action mixer using the two-stage mixing approach (TSMA) developed by Tam *et al*[3]. Sand and CRA were first surface dried in a drying oven at a working temperature of (100 ± 5) ℃, cooled to ambient temperature and then placed in the mixer. After 1 min of mixing, 50 % of the total water was added. After another 1 min of mixing, the four binders were added and mixed for half a minute. Finally, the remaining water with the polycarboxylate superplasticizer (JK-PCA) and the air-entraining agent (AOS) were added and mixed for 2 min. For each mix, 100 mm cubic specimens were cast for compressive strength and frost testing according to GB50107-2010 and GB/T 50082-2009. After demolding after 24 h, the specimens were kept in a standard curing room at a temperature of (20 ± 3) ℃ and a relative humidity of more than 90 % until testing.

The test results have been reported elsewhere[4]. To summarize, the CRA quality can be characterized by its water absorption, and the relationships proposed from this experiment between strength, durability and CRA quality are presented in Sect. 3.3.

3 Mix design procedure

A simple method to obtain the starting composition for the RHPC production using 100% CRA is proposed. This method, which only applies to

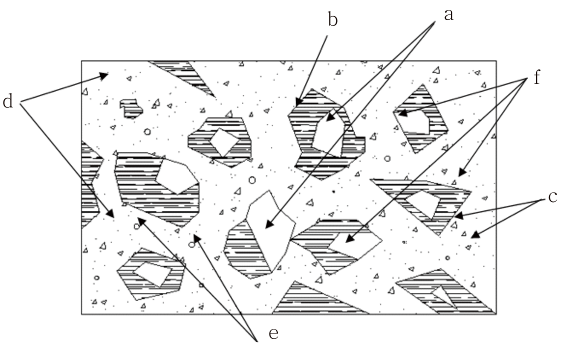
Table 1 Sources, physical properties and quality classes of coarse recycled aggregates

Type	Source	Apparent density/ (kg/m^3)	24 h water absorption/%	Crushing index/%	Na_2SO_4 soundness loss/%	Adhered mortar content/%	Quality class
CRA1	1	2 621	2.8	11.8	3.2	22.8	Ⅰ
CRA2	1	2 483	5.2	14.8	7.8	34.7	Ⅱ
CRA3	2	2 413	4.1	16.7	8.2	40.5	Ⅱ
CRA4	2	2 405	3.7	17.3	7.1	39.4	Ⅱ
CRA5	2	2 395	4.9	16.5	8.6	38.5	Ⅱ
CRA6	2	2 430	6.2	15.7	11.8	44.7	Ⅲ
CRA7	1	2 180	10.3	21.4	14.7	62.6	Below standard

the use of natural sand and nominal maximum sizes of CRAs between 5 and 20 mm, can be applied to RHPC of different compositions, CRA types and frost durability requirements.

3.1 Material constituents and volume model of RHPC using 100% CRA

Compared with natural aggregate concrete, coarse RAC possesses more complex and varying properties due to the use of CRA. The anisotropic and non-homogeneous constituents of coarse RAC are shown in Fig.1. CRA with old mortar attached to its surface tends to be randomly distributed in concrete, which leads to many interfacial transition zones (ITZ) with random distribution. A high water absorption level of CRA may lower the frost resistance of those ITZs between old mortar and other elements. For this reason, it is necessary to limit the maximum water absorption of CRA.



a-coarse recycled concrete aggregate, b-old mortar, c-sand, d-new mortar, e-pores, f- interfacial transition zone

Fig.1 Non-homogeneous constituents of coarse RAC

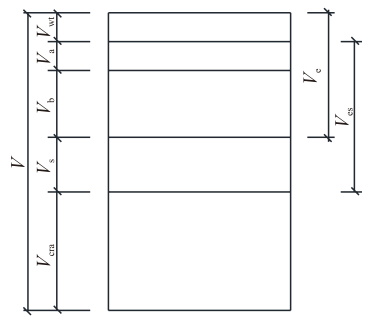


Fig.2 Volume model of RHPC using 100% CRA

A volume model for calculating the content of all elements in HPC was proposed by Chen Jian-kui and Wang Dong-min[5] and applied to RHPC using 100% CRA, as shown in Fig.2. V_{cra} represents the volume of recycled coarse aggregate, V_s, V_{wt}, V_a, V_b, V_e, and V_{es}, are the volume of natural sand, water, air, binder, slurry, and dry mortar, respectively, and V is the total volume of HPC in 1 000 L. The total water volume (V_{wt}) in RHPC consists of the free water volume (V_w) and additional water volume (V_{wa}). The free water is used to ensure the workability of the RHPC and the hydration of the binder, while the additional water is considered to be absorbed by the CRA.

This model is based on three assumptions: 1) the total volume V of HPC remains constant after the hydration reaction with the binder; 2) the voids between the CRAs are fully filled with dry mortar; and 3) the voids between pieces of dry mortar are fully filled with free water.

3.2 Calculation of the sand ratio

As shown in Fig.2, the slurry volume and the dry mortar volume can be expressed by Eq.(1) and Eq.(2), respectively.

$$V_e = V_w + V_a + V_b \tag{1}$$

$$V_{es} = V_a + V_b + V_s \tag{2}$$

The total volume V of RHPC in 1 000 L consists of V_s, V_{cra}, and V_e, leading to Eq.(3):

$$V_s + V_{cra} + V_e = 1\,000 \tag{3}$$

Comparing Eq.(1) with Eq.(2), Eq.(4) can be obtained:

$$V_e - V_w = V_{es} - V_s \tag{4}$$

Eq.(4) can be rewritten as Eq.(5):

$$V_s = V_{es} - V_e + V_w \tag{5}$$

From Eq.(3), the following can be obtained:

$$V_{cra} = 1\,000 - V_s - V_e \tag{6}$$

Substituting Eq.(5) into Eq.(6) yields Eq.(7):

$$V_{cra} = 1\,000 - V_{es} - V_w \tag{7}$$

The sand ratio can then be calculated by Eq.(8):

$$S_P = \frac{S}{S + G_{cra}} = \frac{(V_{es} - V_e + V_w)\rho_s}{(V_{es} - V_e + V_w)\rho_s + (1\,000 - V_{es} - V_w)\rho_{cra}} \times 100\% \tag{8}$$

where S and G_{cra} are the mass of sand and CRA, respectively, and ρ_s and ρ_{car} are their apparent densities.

The void ratio of coarse recycled aggregate can be computed using Eq.(9):

$$P = 1 - \frac{\rho'_{cra}}{\rho_{cra}} \tag{9}$$

where ρ'_{cra} is the bulk density of coarse recycled aggregate.

According to the first two assumptions, the dry mortar volume, V_{es} can be calculated by Eq.(10):

$$V_{\text{es}} = 1\,000P = 1\,000\left(1-\frac{\rho'_{\text{cra}}}{\rho_{\text{cra}}}\right)\times 100\% \quad (10)$$

The optimum slurry volume, V_{e}, is 350 L per 1 000 L of HPC according to Mehta *et al*[6]. Therefore, V_{e} can be expressed by Eq.(11):

$$V_{\text{e}}=350\ \text{L} \quad (11)$$

Substituting Eqs.(10) and (11) into (8), S_{p} is simplified into Eq.(12):

$$S_{\text{P}} = \frac{1}{1+\dfrac{1\,000-1\,000P-V_{\text{w}}}{1\,000P-350+V_{\text{w}}}\cdot\dfrac{\rho'_{\text{cra}}}{\rho_{\text{cra}}}}\times 100\% \quad (12)$$

3.3 Water-absorption-based compressive strength and frost resistance calculation formulas

What distinguishes CRA from coarse natural aggregate is that the former has old mortar attached to its surface. As mentioned in Sect. 2.2, water absorption can be used to characterize the quality of CRA. The relationship developed in Sect. 2 between water absorption and compressive strength is shown in Eq.(13):

$$f_{\text{cu}} = (-3.007\,4x+30.803)\frac{m_{\text{b}}}{m_{\text{w}}}+6.873\,9x-27.97 \quad (13)$$

where f_{cu} is the compressive strength of RHPC at the age of 28 days using 100% CRA, $m_{\text{b}}/m_{\text{w}}$ is the binder-water ratio, and x is the water absorption of the CRA, which corresponds to 1 or 24 h of absorption by the CRA in pure water according to Chinese Code GB/T 17431.2[7]. This effect has been neglected by other workers, such as Chandra and Berntsson[8], who generalize the aggregate absorption in fresh concrete as approximately 75%-100% of the first 30 min to 1 h of absorption in water, and Bogas JA *et al*[9] found a negligible difference between the absorption at 30 and 60 min.

The relationship between water absorption and frost resistance is given in Eq.(14):

$$x_a = \frac{(4.64-0.005\,209n)+\left[(4.64-0.005\,209n)^2-1.482\,8(11.29+0.020\,77n-F_n)\right]^{\frac{1}{2}}}{0.741\,4} \quad (14a)$$

$$x_b = \frac{(0.011\,68n-2.49)-\left[(0.011\,68n-2.49)^2+0.874\,8(96.01-0.003\,413n-P_n)\right]^{\frac{1}{2}}}{-0.437\,4} \quad (14b)$$

where x_{a} and x_{b} are the corresponding water absorption values for F_{n} and P_{n} of CRA respectively, n represents the number of freeze-thaw cycles, and F_{n} and P_{n} are the RHPC compressive strength loss ratio and the relative dynamic modulus of elasticity, respectively, after n freeze-thaw cycles.

Two indices, the quality loss ratio and the relative dynamic modulus of elasticity, both widely used to evaluate the frost durability of HPC prepared with natural coarse aggregate, are not sufficient to evaluate the frost durability of RHPC produced with CRA[10-12]. In particular, the quality loss ratio is determined by the CRA itself due to the high water absorption property of CRA, resulting in cracks in the RHPC after freeze/thaw cycles. The compressive strength loss ratio with a failure value of 60 % ($F_{n\max}$= 60 %), along with a relative dynamic modulus of elasticity with a failure value of 60 % ($P_{n\max}$= 60 %), can reasonably evaluate the frost durability of RHPC with 100% CRA. The failure criterion for RHPC is that failure occurs if either F_{n} or P_{n} reaches its failure limit, $F_{n\max}$ and $P_{n\max}$, respectively. Even when F_n and P_n both reach their failure limits, $F_{n\max}$ and $P_{n\max}$, each at different moments, the two failure values do not appear simultaneously. It is also impossible to obtain equal x_{a} and x_{b}; thus, $x_{\text{a}}\neq x_{\text{b}}$. A frost durability failure of RHPC with 100% CRA can be considered as having occurred when either x_{a} or x_{b} reaches the limit value of $x_{a,\lim}$ or $x_{b,\lim}$. The failure limit value of CRA can by calculated using Eq.(15a) and Eq.(15b):

$$x_{a,\lim} = \frac{(4.64-0.005\,209n_{\max})+\left[(4.64-0.005\,209n_{\max})^2-1.482\,8(11.29+0.020\,77n_{\max}-F_{n\max})\right]^{\frac{1}{2}}}{0.741\,4} \quad 15(a)$$

$$x_{b,\lim}=\frac{(0.011\,68n_{\max}-2.49)-\left[(0.011\,68n_{\max}-2.49)^2+0.874\,8(96.01-0.003\,413n_{\max}-P_{n\max})\right]^{\frac{1}{2}}}{-0.437\,4} \quad 15(b)$$

where $n_{\max}$ is the design maximum number of freeze/thaw cycles.

It is apparent that the water absorption x in Eq.(13) cannot exceed $x_{a,\lim}$ and $x_{b,\lim}$. In addition, x should not exceed 8 % in accordance with China Standards GB/T 25177-2010[13]: Recycled Coarse Aggregate for Concrete, in which 8% is the maximum allowable value for water absorption of CRA for the lowest class, Class Ⅲ.

Therefore, the restrictions on the value of x can be expressed by Eq.(16):

$$x \leqslant x_{\lim}=\max\{x_{a,\lim}, x_{b,\lim}, 8\%\} \quad (16)$$

3.4 Calculating the water content

From Eq.(13), m_b/m_w can be computed as shown in Eq.(17):

$$\frac{m_b}{m_w}=\frac{f_{cu}+27.97-6.873\,9x}{30.803-3.007\,4x} \quad (17)$$

Then, the volume of binder can be obtained as shown in Eq.(18):

$$V_b=\frac{m_b}{\rho_b}=\frac{m_b}{m_w}\cdot\frac{m_w}{\rho_b}=\frac{f_{cu}+27.97-6.873\,9x}{30.803-3.007\,4x}\cdot\frac{\rho_w V_w}{\rho_b} \quad (18)$$

where ρ_b is the apparent density of the binder, computed by Eq.(19a) or (19b). α_i and β_i are the volume fraction and mass fraction of the i^{th} binder, respectively:

$$\rho_b=\alpha_1\rho_1+\alpha_2\rho_2+\cdots+\alpha_n\rho_n \quad (19a)$$

$$\rho_b=\frac{1}{\frac{\beta_1}{\rho_1}+\frac{\beta_2}{\rho_2}+\cdots+\frac{\beta_n}{\rho_n}} \quad (19b)$$

Substituting Eq.(18) into Eq.(1), the free water content V_w can be determined as shown in Eq.(20):

$$V_w=\frac{350-V_a}{1+\frac{f_{cu}-6.873\,9x+27.97}{30.803-3.007\,4x}\cdot\frac{\rho_w}{\rho_b}} \quad (20)$$

3.5 Mix proportion design procedure

Given the design requirements of workability (slump SL and slump flow SF), strength class ($f_{cu,k}$), and frost durability ($n_{\max}$), the mix proportion design can be conducted using the following method.

a) Considering the required frost durability, $n_{\max}$, calculate the limit value of water absorption of CRA, $x_{\lim}$, using Eqs.(15a) and (15b).

(2) Test the actual water absorption, x, of the CRA. If $x > x_{\lim}$, choose the next recycled coarse aggregate until $x \leqslant x_{\lim}$.

(3) Considering the required compressive strength, $f_{cu,k}$, calculate f_{cu} using Eqs.(21a) or (21b):

$$f_{cu}=f_{cu,k}+1.645\times\sigma \quad (f_{cu,k}<60\text{ MPa}) \quad (21a)$$

$$f_{cu}=1.15f_{cu,k} \quad (f_{cu,k}\geqslant 60\text{ MPa}) \quad (21b)$$

The standard deviation σ in Eq.(21a) can be obtained by statistics; alternatively, $\sigma \geqslant 5.0$ MPa can be used for $f_{cu,k}$= 25-45 MPa, or $\sigma \geqslant 6.0$ MPa for $f_{cu,k}$= 50-55 MPa.

(4) Calculate m_b/m_w using Eq.(17).

(5) Calculate the water volume V_w using equation (20), the free water mass $m_w=V_w\times\rho_w$, the total water mass $m_{wt}=m_w+m_{wa}=m_w+xm_w$, where m_{wa} is the additional water mass, and the recycled coarse aggregate mass $m_{cra}=\rho_{cra}(1\,000-1\,000P-V_w)$.

(6) Calculate the sand ratio S_p using Eq.(13) and the sand mass $m_s=\frac{S_P}{1-S_P}\times m_{cra}$.

(7) Calculate the total binder mass, $m_b=\frac{v_w\cdot\rho_w}{m_w/m_b}$, and each individual binder mass using their mass percentages.

(8) Calculate the masses of the other materials such as the superplasticizer, the air-entraining agent and any other materials used.

4 Application examples and discussion

Five examples of RHPC with 100 % CRA with different workability, strength class and frost durability values are now presented. The information on the design requirements and CRA used is listed in Table 2, and the mix proportion and test results are shown in Table 3.

Table 2 shows that all results, including the workability, strength and frost resistance, for the five examples are satisfactory. The suggested method does not require previous trial tests and thus increases the efficiency. At most, a water absorption check is

Table 2 Design requirements and CRA used for five application examples

No.	Design index			Choice of CRA type
	$f_{cu,k}$/MPa	n_{max}	SL/(cm) × SF/(cm)	
1	40	400	15×25	CRA6
2	50	500	18×30	CRA2
3	60	600	25×40	CRA3
4	70	700	35×55	CRA4
5	80	800	45×75	CRA1

Table 3 Mix proportion and test results for five application examples

No.	Mix proportion/(kg/m^3)									Test result		
	Cement	Silica fume	Fly ash	Slag	CRA	Sand	Water	JK-PCA	AOS	f_{cu}	n_{max}	SL/(cm) × SF/(cm)
1	265	20	82	41	1 049	615	156(63) *	0.6	1.2	48	450	18×27
2	290	22	89	45	1 026	665	143(62) *	1.8	1.3	56	560	22×35
3	316	24	97	49	1 118	545	128(67) *	2.7	1.5	65	650	27×41
4	356	27	109	55	1 041	544	107(62) *	5.5	1.6	78	730	38×65
5	380	29	117	58	1 108	486	94(66) *	6.8	1.8	87	840	51×79

* Note: water content consists of free water (additional water)

needed to judge the CRA applicability to the design requirements of RHPC, regardless of the concrete waste source and CRA quality class.

5 Conclusions

A simplified method for designing the mix proportion of RHPC using 100% recycled coarse aggregate has been developed based on the frost durability. Compared to the existing design procedures, the suggested method possesses two distinct advantages: i) rather than extensive trial tests, a water absorption test is sufficient to determine whether the CRA can produce RHPC with the expected high workability, high strength and high frost durability; ii) all constituents of RHPC are obtained by calculation rather than empirically.

Three formulas are introduced, the water absorption limit value, x_{lim}, for the frost durability design index, defined by the number of required freeze/thaw cycles n_{max}; the tolerant compressive strength loss F_n after n_{max} freeze/thaw cycles, calculated using the water-binder ratio and water absorption; and the sand ratio.

In summary, a new mix design procedure has been defined for RHPC with natural sand that is valid for any type of CRA and can be easily implemented in practice. Our method may contribute to a simpler and more efficient design of structural recycled aggregate concrete.

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