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Investigation of the mix ratio design of lightweight aggregate concrete

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Abstract

According to the analysis of the domestic and overseas researches and achievements of lightweight aggregate concrete, a new strength formula on account of tube compressive strength of lightweight aggregate and glue–capacity ratio is put forward on the mix ratio design of lightweight aggregate concrete. The conception of concrete filler coefficient is also proposed, the theoretical formula of sand–aggregate ratio is deduced and the quasi-principle of stationary water consumption by considering the working character of concrete is summarized. Therefore, the designing equation of mix ratio of lightweight aggregate concrete which is tested by some further experiments is defined.

Keywords: Concrete; Tube compressive strength; Sand–aggregate ratio; Glue–capacity ratio

Since 1956, the research of lightweight aggregate and lightweight aggregate concrete has been introduced in China, but not until 1980 (under Gong Luoshu and other experts [1,2]) was it researched systematically. However, by now, the methods of mix ratio designs used as determined by looking for charts and tables to test the design should be finalized.

1. The formula of concrete compressive strength

Nowadays, there are two equations of compressive strength of lightweight aggregate concrete [8,9]:

$$R_{28} = \frac{b_1 \times C}{W} + b_2 \times \gamma_K + b_3 \times V_Q + a' \qquad (1)$$

where R_{28}—28-day compressive strength of lightweight aggregate concrete, MPa; C/W—effective water–cement ratio of lightweight aggregate concrete; γ_K—particle density of lightweight coarse aggregate; V_Q—actual consumption of lightweight aggregate; b_1, b_2, b_3, a'—experimental parameters;

$$R_{28} = b_1 \times R_C + \frac{b_2 \times C}{W} + b_3 \times R_T - a' \qquad (2)$$

where R_C—actual strength of cement, MPa; R_T—tube compressive strength of lightweight aggregate, MPa; others as the former formula.

The two equations only reflect the contribution to the strength of the different factors through orthogonal design, but they are not coincident with each other in the dimensional analysis.

The difference of aggregate between lightweight aggregate concrete and common concrete makes it different to design their mix ratio [4]. Because the lightweight aggregate concrete can influence the dry apparent specific gravity but the dry apparent specific gravity of common concrete is almost a constant, the apparent specific gravity of lightweight aggregate concrete can influence the concrete compressive strength greatly. Also because the differences in specific absorption rates of lightweight aggregates influence the water consumption of concrete, and the influence of specific absorption of common aggregate can be ignored, it is very difficult to measure the net water–cement ratio or efficient water–cement ratio accurately. For

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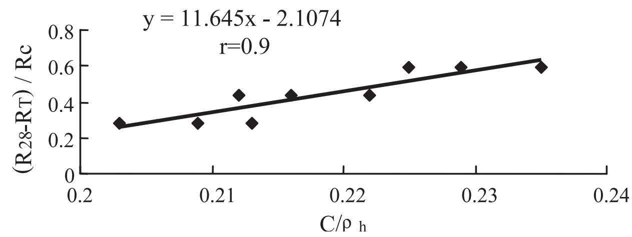

Fig. 1. Regression analysis of strength formula of lightweight aggregate concrete.

lightweight aggregate concrete, the concrete strength formula by using the relationship between concrete strength and cement consumption to satisfy the consistency is more convenient and accurate than the one which is indicated by water–cement ratio [3]. Summarizing the influence of dry apparent specific gravity and the cement consumption of lightweight aggregate concrete, we consider the proportion of cement consumption C and apparent specific gravity ρ_h of light aggregate concrete or called glue–capacity ratio C/ρ_h as the most important parameter.

The influence of different lightweight aggregates on concrete strength is greater than that of common concrete. The strength of aggregate of common concrete is 1.5–2.0 times harder than the strength of concrete by itself, while the strength of lightweight aggregate is far lower than that of concrete, so they have different destructive forms if compressed. The destructive form of the former is mainly on the boundary of aggregate and that of the latter is both on the aggregate boundary and the aggregate itself. So it is important to contribute to the strength for tube compressive strength of lightweight aggregate [6,7].

As a result, the strength equation of lightweight aggregate concrete is as follows:

$$\frac{R_{28} - R_T}{R_C} = a \times \frac{C}{\rho_h} + b \qquad (3)$$

where ρ_h—dry apparent specific gravity of lightweight aggregate concrete; a, b—experimental parameters.

From Fig. 1, we can draw this conclusion: a=11.645; b=−2.107.

2. Filler coefficient and sand–aggregate ratio

The changes of sand–aggregate ratio which can change the total superficial area of aggregate and the percentage of voids among aggregates can influence the working character of concrete; the orthogonal experiments of the relationship between sand–aggregate ratio and concrete compressive strength show that the influence is slightly when the sand–aggregate ratio is 28–42%, so based on the difference of concrete strength and working character, we can regulate the consumption of light and coarse aggregate by selecting sand–aggregate ratio in order to get good working character and without compromising the strength of concrete [1]. When considering the concrete density and cement reduction, there is a reasonable sand–aggregate ratio or called optimum sand–aggregate ratio. J.D. Bamal and J. Mson's experiments prove that the natural filler coordination number of maximum aggregate is 5–6, the vibrating filler coordination number is 6–7, and also the observed value of natural filler air voids is 0.395, and the experimental value is 0.400 when the coordination number is 6 [4]. Its value is equal to the filler volume of sand and cement paste, that is to say, the mortar volume is as follows:

$$V_S = 0.400 - \frac{C}{\rho_C} - \frac{W}{C}$$

where C—the cement consumption, ρ_C—the cement density, W—the water consumption; ρ_W—the water density.

The equation also can be regulated as follows:

$$V_S = 0.400 - C \times \left(\frac{1}{\rho_C} + \frac{W}{C}\right) \qquad (4)$$

When Eq. (4) is divided by the total consumption of lightweight and coarse aggregate, we can get the common formula as follows:

$$S_P = A_0 - B_0 \times n^{-1} \times \left(\frac{1}{\rho_C} + \frac{W}{C}\right) \qquad (5)$$

where n—aggregate–cement ratio.

From the deduction of Eq. (5), we can see that the influence coefficient A_0 is the filler coordination number and the influence coefficient B_0 shows that sand–aggregate ratio depends on the water–cement ratio W/C and also reflects the filler extent of cement mortar filling the aggregate air-gap and the influence of cement–aggregate ratio, different types of cements and lightweight aggregate.

For the uncertainty of W/C of lightweight aggregate concrete, W/C can be replaced by C/ρ_h , so Eq. (5) is as follows:

$$S_P = A_0 - B_0 \times n^{-1}\left(\frac{1}{\rho_C} + \frac{c}{\rho_h}\right) \qquad (6)$$

where n—glue–capacity ratio; ρ_h—dry apparent specific gravity.

For the lightweight aggregate concrete, aggregate–cement ratio n is about 3–4. Based on the experimental results (Table 2), the average of aggregate–cement ratio n is 3.45. That is, n=3.45.

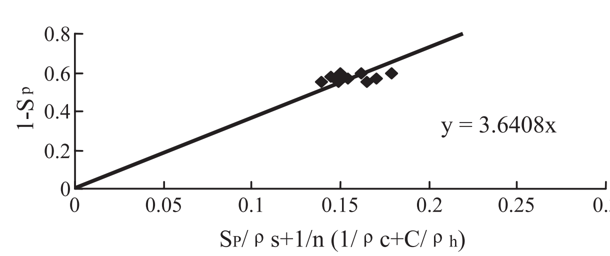

Fig. 2. Curve of filler coefficient e_s of lightweight aggregate concrete.

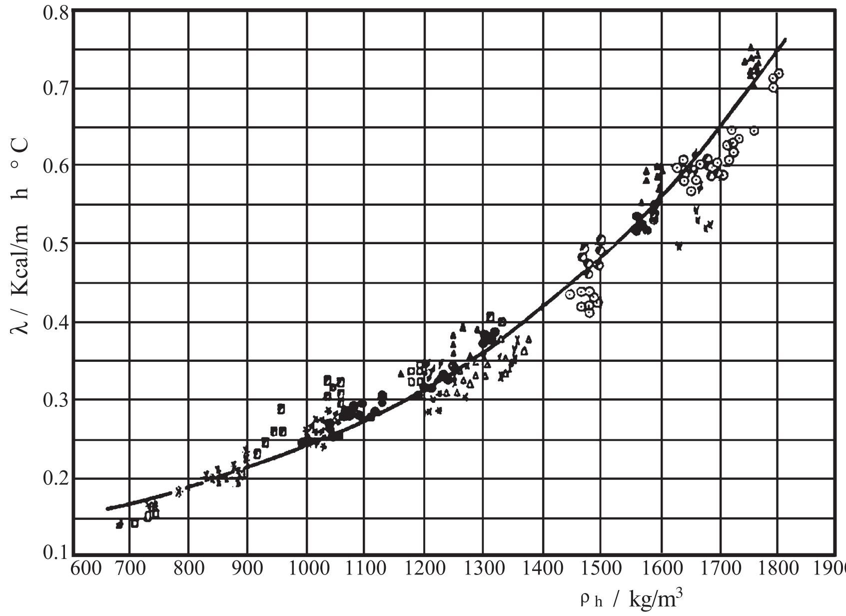

Fig. 3. Coefficient of heat conductivity λ and volume weight ρ_h of lightweight concrete under dry conditions. (-) fly-ash ceramsite concrete (Tianjin); (⊙) fly-ash ceramsite concrete (Xi'an); (□) pumice concrete (Jilin); (▲) natural coal stone concrete (Lingning); (△) pumice concrete (Ha'erbin); (★) perlite ceramsite concrete (Neimeng); (x) broken brick concrete; (◪) shale ceramsite concrete; (◐) clay ceramsite (Tuqiao); (●) saltern ceramsite concrete (Dagang); (●) cindery concrete (Jilin); (※) large particle perlite concrete.

According to the researches of Professor Wang Liju, $A_0=(1+e_s/\rho_s)^{-1}$, $B_0=A_0\times e_s$. e_s is the filler coefficient of concrete [5], just as Fig. 2 shows. ρ_s is the apparent specific gravity of sand. We can see in Fig. 2 that: $e_s=3.641$.

3. Design of mix ratio and experimental test

3.1. Design of mix ratio

There are two methods of mix ratio design of lightweight aggregate: loose volume calculations and absolute solid volume calculations. The mix ratio design of this paper is based on the loose volume of light and coarse aggregate per cubic concrete, then rectified, experimented and adjusted according to the dry apparent specific gravity of concrete with design requirement.

3.1.1. The determination of apparent specific gravity of lightweight aggregate

Because lightweight aggregate concrete is used mostly in the energy conservational manufactures of concrete, its apparent specific gravity is derived by the requirement of heat impedance or coefficient of heat conductivity. The apparent specific gravity can be obtained from Fig. 3, which is based on the experimental results of Bai Yuzhen [1].

$$\lambda_{dry} = 0.0725e^{0.00128[\rho_h]} \quad (7)$$

where λ_{dry}—coefficient of heat conductivity of lightweight concrete, W/m °C.

3.1.2. The determination of cement consumption

Firstly, according to the design of strength formula, we can get the trying strength R, then C/ρ_h based on the strength formula of lightweight aggregate concrete, and then we get the cement consumption C.

$$R = R_{design} + 1.645\sigma \quad (8)$$

where σ—deviation difference, 1.645 is the probability when guarantee ratio is 95%.

From Eq. (4), we can derive the following equations:

$$\frac{C}{\rho_h} = \frac{\dfrac{R_{28}-R_T}{R_C} - b}{a}$$

$$C = \frac{[\rho_h] \times C}{\rho_h}$$

Table 1
Physical mechanics of ceramsite

Cumulose density, kg/m^3	Apparent specific gravity, kg/m^3	1hw absorption rate, %	Tube compressive strength, MPa	Grain grade, %				
				16–20	10–16	5–10	2.5–10	<2.5
415	830	8	0.8	5.4	16.5	46.8	30.6	0.1

Table 2
Experimental mix ratio with fly-ash

No.	Unit dosage, kg/m^3							Aggregate–cement ratio n	Sand–aggregate ratio S_P	Glue–capacity ratio C/ρ_h	Water–cement ratio W/C	Slump, cm
	C	F	S	G	W		Mixture					
					W0	1hw						
1	175	245	979	343	159	27	17.5	3.78	0.45	0.203	0.45	18
2	185	259	979	342	163	27	18.5	3.57	0.45	0.212	0.44	18
3	200	280	935	355	199	28	20	3.23	0.43	0.229	0.5	>20
4	175	245	870	374	175	30	17.5	3.55	0.4	0.213	0.5	>20
5	185	259	870	374	148	30	18.5	3.36	0.4	0.222	0.4	13
6	200	280	870	374	180	30	20	3.11	0.4	0.233	0.45	18
7	175	245	914	361	150	29	17.5	3.64	0.42	0.209	0.43	16
8	185	259	935	355	185	28	18.5	3.49	0.43	0.218	0.5	>20
9	200	280	979	342	160	27	20	3.30	0.45	0.225	0.4	16

W0 is net water–cement ratio, 1hw is 1 h water absorption.

3.1.3. The determination of consumption of light and coarse aggregate

If the total volume V_{SG} of lightweight and coarse aggregate is known, then the volume V_G of coarse aggregate and the volume V_S of lightweight aggregate can be derived from the following equation

$$S = V_{SG} \times S_P \times \rho_S \tag{9}$$

$$G = V_{SG} \times (1 - S_P) \times \rho_G \tag{10}$$

where ρ_S—the cumulose density of lightweight aggregate, ρ_G—the cumulose density of coarse aggregate.

3.1.4. The determination of unit water consumption

If controlling the working character of lightweight aggregate concrete, especially if the liquidity is to be controlled in order to satisfy the pumping requirement, then the slump is about 16–18 cm, and the unit water consumption is a constant which is defined as about 160 kg/m^3 by experiments.

3.1.5. The verification of dry apparent specific gravity

From the consumptive calculation of lightweight aggregate, coarse aggregate and cement, we adjust and verify the dry apparent specific gravity of lightweight aggregate concrete as follows:

$$\rho_h = 1.15C + S + G \tag{11}$$

If $|\rho_h - [\rho_h]|/[\rho_h] > 5\%$, then $[\rho_h]$ needs to be calculated again, by repeating the former calculation.

Table 3
Experimental mix ratio without fly-ash

No.	Consumption of per cubic meter, kg			
	C	S	G	W
1	320	810	308	185
2	350	782	316	185
3	345	792	542	187
4	365	765	555	188
5	390	735	570	188.5

3.2. Experimental test

3.2.1. Raw and processed materials

Cement: no. 32.5 Portland cement made in Dalian Xiaoyetian Cement Industry.
Fly-ash: fly-ash made in Tieling Power Industry, mix rate is 50% (for the need of environmental protection, or can be omitted).
Lightweight aggregate: shale ceramsite made in Jilin, its physical mechanics is listed in Table 1.

3.2.2. Design of mix ratio

The mix ratio is listed in Table 2 (with fly-ash) and Table 3 (without fly-ash).

3.2.3. Analysis of experimental results

The analysis of experimental results is listed in Table 4. The comparison of experimental results and design results is shown in Fig. 4.

4. Conclusions

(1) The basic parameters of the design of mix ratio of lightweight aggregate are sand–aggregate ratio S_P, glue–

Table 4
Experimental results

No.	1	2	3	4	5	6
R_{28} design value (MPa)	10	15	10	15	10	15
R trying strength (MPa)	14.9	19.9	14.9	19.9	14.9	19.9
R_{28} experimental value (MPa)	13.5	15.6	18.3	17.9	11.6	19.5
R_{28} design value (MPa)	10.0	15.0	20.0	25.0	30.0	
R_{28} experimental value (MPa)	12.3	16.5	20.9	25.5	31.1	

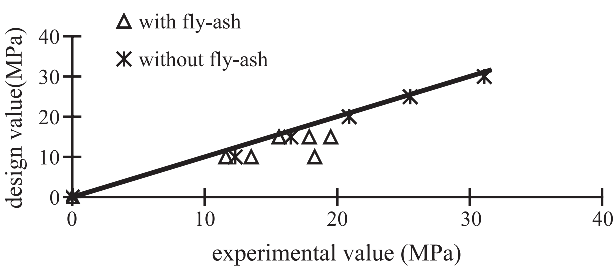

Fig. 4. The comparison of experimental value and design value.

capacity ratio C/ρ_h and unit water consumption or constant water consumption W. Though the principle of water–cement ratio is suitable for lightweight aggregate concrete, it is very difficult to measure the saturated surface-drying apparent specific gravity of aggregate. Because net water–cement ratio is related not only with the water content of aggregate, but also with the velocity of water absorption when mixed, it is difficult to use the water–cement ratio to design the mix ratio, and glue–capacity ratio C/ρ_h can replace cement–water ratio C/W.

(2) Analyzing that the relative strength $(R_{28}-R_T)/R_C$ is in direct proportion to glue–capacity ratio C/ρ_h when considering tube compressive strength, Eq. (4) is derived.

(3) The unit water consumption of lightweight aggregate concrete should use tentative standard water consumption whose value is about 160 kg/m^3 which can satisfy the requirement of working character of whose slump is 16–18 cm; volume sand–aggregate ratio is mostly based on glue–capacity ratio C/ρ_h, aggregate–cement ratio n, and the different kinds of cements and types of sands; aggregate–cement ratio n is about 3.45 based on the experimental results.

(4) Based on the theory of dense filler, the formula of theoretical sand–aggregate ratio S_P is derived where the filler coefficient e_s is the main norm of sand–aggregate ratio S_P when the glue–capacity ratio C/ρ_h and aggregate–cement ratio n are constant and the basic influence coefficient of e_s is the largest grain size of coarse aggregate.

References

[1] Researches and applying collected works of lightweight aggregate concrete, Building Construction Institute of Building Science Academy, Beijing, Chinese Building Publishing House, 4/1981.

[2] L. Gong, Applying Handbook of Concrete, Chinese Building Publishing House, Beijing, 5/1995, second publishing.

[3] S. Popovic, Newly Mixed Concrete, Chinese Building Publishing House, Beijing, 10/1990.

[4] C. Liu, et al., Aggregate Character and Manufacturing Technology of Concrete, Publishing house of South-West University of Technology, Guangzhou, 8/1999.

[5] L. Wang, M. Cao, H. Ai, Study on the Infilled Aggregate Coefficient in Ordinary Concrete, Concrete, Shengyang, 2002, No. 8, pp. 9–11.

[6] B. Schulz, Design of Lightweight Aggregate Concrete According to the Known Strength, Beton, second edition, 1977, translated by Xiuyu Ye.

[7] K. Wesche, Physical Principles for the Design of Lightweight Concrete Structures, Beton, Stahlbetonbau 62, 1957, No. 11, pp. 256–260.

[8] H. Weigle, S. Karl, Mix Ratio Design of Lightweight Aggregate Concrete, Lightweight Aggregate Concrete CEB/FIP Manual of Design and Technology, pp. 23–47.

[9] P. Beckman, M.E.R. Little, et al., Design of Lightweight Aggregate Concrete Construction, Lightweight Aggregate Concrete CEB/FIP Manual of Design and Technology, pp. 101–114.