Pergamon

Cement and Concrete Research 29 (1999) 331–337

CEMENT AND CONCRETE RESEARCH

How to design concrete produced by a two-stage concreting method

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Manuscript received 8 May 1998; accepted manuscript 6 November 1998

Abstract

Two-stage concreting is produced by placing stone aggregate in a form and later injecting grout (water, cement and sand), usually with admixtures, to fill the voids. Due to lower costs and acceleration of performance of many constructions, the two-stage concrete has been used more and more often. The compressive strength of the two-stage concrete depends mainly on the strength of stone aggregates, so that, the commonly used formulae for compressive strength of traditional concrete are not valid. Moreover, there is no information on the design of such concrete. The aim of this paper is to propose an algorithm for the design concretes made by two-stage method.

Keywords: Aggregate; Grout; Concrete; Compressive strength

The first trial application of two-stage concreting was performed by Wertz for the Pentagon in USA (called Prepakt [1,2]). The name of the two-stage method is given to a method of concreting in which the stone aggregate is first placed in the moulds and then grouted with a specially prepared grout. It can be used for plain concrete or reinforced concrete, for large mass concrete, for work where the reinforcement is very complicated, and for placement under water.

The technology of concretes made by the two-stage method is quite different from normal traditional concrete, not only in the method of placement but also in that it contains a higher proportion of stone aggregate. Because of the point-to-point contact of the stone aggregate, the stresses are transferred first to the stone aggregate and then, after deformations of grains, to the hardened grout.

There is a possibility of making concrete produced by a two-stage method less expensive by 25% to 40% of the total costs compared with that for traditional concrete [3,4].

This paper presents an algorithm for the design of concretes made by the two-stage method. The laboratory tests involved 800 samples of 40 × 40 × 160 mm tested for the compressive strength of grout, as well as 647 concrete cubic samples of 300 × 300 × 300 mm, tested for compression at 28 days. The parameters in this investigation were three different aggregates (rounded, crushed, and mixed); four water-to-cement (w/c) ratios of 0.40, 0.45, 0.50, and 0.55; three cement-to-sand (c/s) ratios of 1/1.5, 1/1, and 1/0.8; and three mixings in an Ultramixer for 2, 4, and 6 min.

1. Experimental details

1.1. Materials

Portland cement C35 with fly ash, produced by the Gurażdże cement plant (Poland) and conforming to Polish specifications [4] was used in these investigations.

The fine aggregate used in the manufacture of the grout was clean sand brought from a quarry at Borowiec near Gdańsk, Poland. The fine aggregate was natural and dry; the largest particles of the sand did not exceed the size that passes through a No. 2 sieve (2 mm), conforming to Polish specifications [3,4].

1.1.1. Stone aggregate

The choice of stone aggregate is of great importance with respect to the two-stage method. According to the known properties, three types of stone aggregate were used: rounded aggregate, crushed (basalt) aggregate, and mixed aggregate (by volume, rounded to crushed 1:1). The stone aggregate was washed. The maximum size of the stone aggregate should not be larger than one third of the minimum dimension of the mould [3,5]. The physical properties of the stone aggregate are shown in Table 1.

Superplasticizer type Betoplast 1 (product of Poland) was used for all mixes and was added at a rate of 2% by weight of cement (its original chemical composition was

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PII: S0008-8846(98)00215-4

Table 1
Physical properties for stone aggregate

Kind of stone aggregate	Loose density (kg/L)	Crushing strength (f) (N/mm^2)			Apparent specific gravity	Void ratio (%)	Absorption (%)	Grain size (mm)
		Test no.	f	Average f				
Rounded	1.58	1	10.18	10.74	2.607	39.0	0.62	16–100*
		2	11.31					
		3	10.75					
Crushed	1.43	1	14.14	14.14	2.687	47.0	0.34	16–63
		2	13.58					
		3	14.71					
Mixed	1.50	1	12.16	12.72	2.641	43.0	0.56	16–100*
		2	13.58					
		3	12.44					

* The quantity of the greatest grain from 80 to 100 mm did not exceed 8%.

registered in the State Patent Office as an invention project under No. PN-265898 in 1987 [4,6]).

1.2. Preparation of specimens

Stone aggregate, before placing in moulds, was saturated surface dry at the time of grout injection (first stage). Then the grout prepared in a high-speed mixer (Ultramixer) was injected into the voids of the stone aggregate (second stage). The rotor speed of the Ultramixer was 3000 rpm and the nominal capacity 120–130 L, yielding an average mixing rate of 4500–6000 L/h. The Ultramixer was turned on before adding the mixing water and then Betoplast 1, cement, and fine sand. The grout was mixed for 2, 4, and 6 min after all ingredients had been added [7,8]. Before putting the stone aggregate into moulds, it was subjected to cavity testing, and the volume of free space between the grains was measured in a 50-L vessel. The vessel was filled with stone aggregate to the top level without compacting or shaking. The final step was to fill the voids with water. Volume of the poured water divided by the vessel volume gave the final void ratio value. The results are shown in Table 1. Void ratio is an important parameter of stone aggregate, because it defines the quantity of grout.

After 24 h of curing time, the concrete specimens were removed from the moulds and covered with wet burlap for 7 days. Specimens were stored in open air (in the laboratory) at 18°C ± 2°C for 28 days.

1.3. Mix proportions

The mix proportions of the grout were prepared at w/c ratios of 0.40, 0.45, 0.50 and 0.55, and c/s ratios of 1/1.5, 1/1, and 1/0.8. Betoplast 1 was used for all mixes and was added at a rate of 2% by weight of cement.

1.4. Method of testing

1.4.1. Fluidity tests

Determination of the flow of a grout of the required fluidity is linked directly to the injection of this grout into the stone aggregate. The test method measures the flow of the injected grout placed in a cylinder of 0.25-L volume when poured onto a scaled plate from a height of 10 mm [3,4]. The measurement of grout fluidity is the diameter of the spread. Three readings of fluidity were made in all measurement series.

1.4.2. Sedimentation tests

Sedimentation influences decrease of the adherence force between the grout and the stone aggregate grains. The grout is poured in quantities of about 500 mL into three graduated cylinders of 1000-mL volume. After 3 h, the depth of the water layer on the grout is measured. Sedimentation is the ratio of the depth of the water layer to the height of the grout after pouring into the cylinders [3,9]. Three readings of sedimentation were made in all measurement series.

1.4.3. Concrete strength tests

The compressive strength of grout ($\overline{f}_g$) was tested by using a hydraulic machine of 1600-kN capacity. Measurements of the compressive strength of the two-stage concrete ($\overline{f}_c$) were taken using a hydraulic testing machine, adjusted for the load range 0–4000 kN.

The measured concrete strength ($\overline{f}_c$) and grout strength ($\overline{f}_g$) results of each series were averaged and readings ±15% from the mean were rejected [1]. Twelve readings of grout strength ($\overline{f}_g$) and six readings of concrete strength ($\overline{f}_c$) were made in all measurement series.

2. Statistical analysis of laboratory test results

The main objective of the statistical analysis is to predict the strength of the concrete at 28 days from the parameters of the grout and the aggregate as measured in laboratory using the program STATISTICA® for Windows.

The statistical analysis of experimental laboratory data was carried out using a nonlinear regression method. The calculations were carried out for each series of laboratory examinations. Based on the elementary equations and their coefficients the following functions have been elaborated:

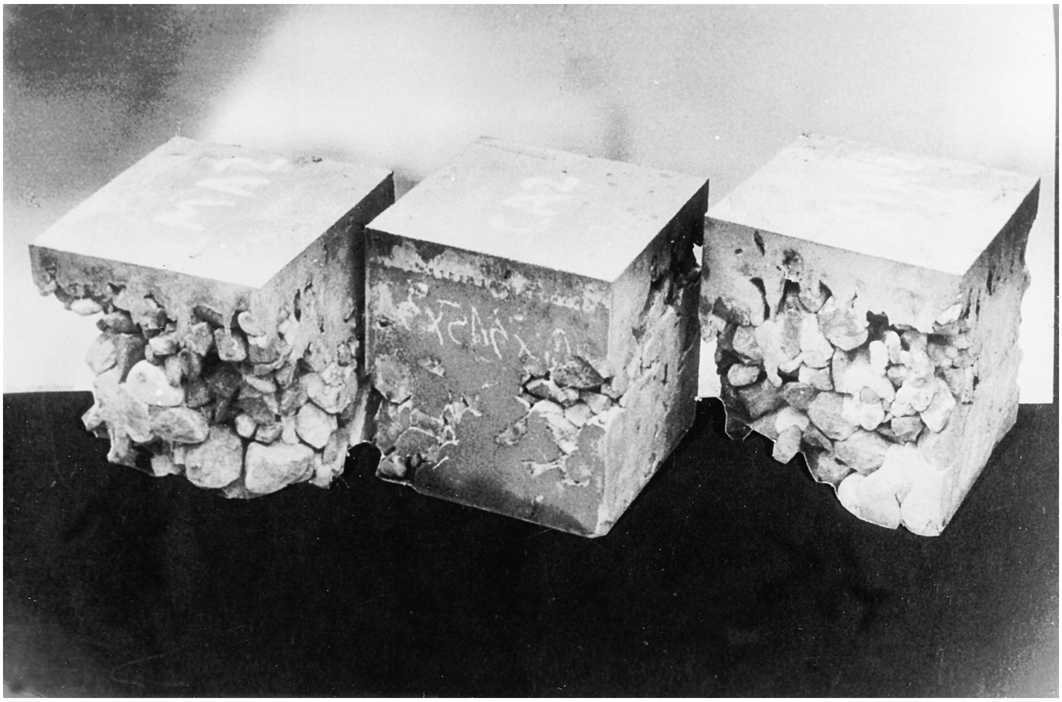

Fig. 1. After grouting, the concrete was honeycombed at w/c ratio = 0.40 and c/s ratio = 1/1.5.

1. Sedimentation = f(w/c ratio, c/s ratio, and time of mixing)
2. Fluidity = f(w/c ratio, c/s ratio, and time of mixing)
3. $\overline{f}_g$ = f(w/c ratio, c/s ratio, and time of mixing)
4. $\overline{f}_c$ = f(w/c ratio, c/s ratio, and time of mixing) for rounded, crushed, and mixed aggregate
5. $\overline{f}_c$ = f($\overline{f}_g$) for rounded, crushed, and mixed aggregate.

By fitting to empirical points simple functions that most exactly reflect the shape of dependence, from the equations were chosen and the correlation between the calculated and observed results for the dependencies was found the best, using a quasi-Newton estimation method [Eq. (1)]:

$$\text{Loss function} = \sum (y_{\text{experimental}} - y_{\text{computed}})^2 . \quad (1)$$

3. Analysis of investigation results

3.1. Sedimentation

The percentage of sedimentation increases with an increase of w/c ratio, but if the w/c ratio is constant, the sedimentation value falls with an increase in the duration of mixing. It is clear a mixing time of >4 min exerts a slight influence on the course of the phenomenon. With an increase of sand in the grout, a slow decrease of the sedimentation value was observed. For w/c ratio = 0.40 and c/s ratio = 1/1.5 (see Mix proportions) the sedimentation was equal to 0%, because the grout was too thick and could not penetrate to all the voids of the stone aggregate (Fig. 1). It is assumed that, for practical application, the w/c ratio contained within the range of 0.45–0.55 at c/s ratio = 1/1.5 is good. For sedimentation an empirical general equation was calculated as given in Eq. (2):

$$\text{Sedimentation} = (a_0 + a_1 * (w/c)^{a_2}) * (a_3 + a_4/\text{time}) * (a_5 + a_6 * (c/s)^{a_7}) \ (\%) \quad (2)$$

where w/c ratio = 0.40, 0.45, 0.50, and 0.55; c/s ratio = 1/1.5, 1/1, and 1/0.8; time of mixing = 2, 4, and 6 min; and $a_0, a_1, \ldots, a_7$ = constants obtained from regression analysis. Their values are given in Table 2.

The range of the general Eq. (2) is 1% ⩽ sedimentation < 7%.

Table 2
Regression constants of sedimentation Eq. (2)

No. of readings	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7	Coefficient of correlation
108	−0.21	3.01	2.18	4.07	10.89	0.59	0.30	3.27	0.972

Table 3
Regression constants of fluidity Eq. (3)

No. of readings	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7	Coefficient of correlation
99*	2.96	27.82	2.26	2.52	1.13	−3.87	8.03	0.24	0.977

* Does not include w/c ratio = 0.40 at c/s ratio = 1/1.5 in the general Eq. (3).

Table 4
Regression constants of $\bar{f}_g$ Eq. (4)

No. of readings	α_0	α_1	α_2	α_3	Coefficient of correlation
432	90.88	−117.97	3.56	0.61	0.982

3.2. Fluidity

Investigation of the diameter change of grout flow on the target surface indicated that for activation times of 2, 4, and 6 min, the tested equivalent has variable values. At mixing time longer than 4 min, the grout thickens and the flow is reduced (the same behaviour as sedimentation). For w/c ratio = 0.40 and c/s ratio = 1/1.5, the grout does not exhibit any fluidity; it has a plastic consistency and does not penetrate to all the voids of the stone aggregate (Fig. 1). However, for w/c ratio = 0.40 and c/s ratio = 1/1, it was characterized by partial fluidity, because the grout was leaking from a funnel. For fluidity an empirical general equation was calculated as given in Eq. (3):

$$\text{Fluidity} = (b_0 + b_1 * (w/c)^{b_2}) * (b_3 + b_4/\text{time}) * (b_5 + b_6 * (c/s)^{b_7}) \quad (\text{mm}) \qquad (3)$$

where $b_0, b_1, \ldots, b_7$ are constants obtained from regression analysis and are given in Table 3.

The range of the general Eq. (3) is 70 mm $\leqslant$ fluidity $<$ 140 mm.

3.3. Compressive strength of grout ($\bar{f}_g$)

Compressive strength ($\bar{f}_g$) increases with the duration of mixing. It increases for all w/c ratios, because of less sedimentation and an increase of the specific surface area of cement, which becomes finer due to high-speed mixing in the Ultramixer. From the beginning, with c/s ratio = 1/1.5 and a decrease of sand in the grout, the compressive strength ($\bar{f}_g$) increases slightly. For compressive strength of the grout an empirical general equation was calculated as given in Eq. (4):

$$\bar{f}_g = \alpha_0 + \alpha_1 * (w/c) + \alpha_2 * (c/s) + \alpha_3 * \text{time} \quad (\text{N/mm}^2) \qquad (4)$$

where $\bar{f}_g$ = compressive strength of grout at 28 days (N/mm^2), and $\alpha_0, \ldots, \alpha_3$ are constants obtained from regression analysis and are given in Table 4.

3.4. Compressive strength of two-stage concrete ($\bar{f}_c$)

Dependence of concrete strength ($\bar{f}_c$) on cement quantity is different than in traditional concretes. The cement quantity of two-stage concrete depends on the void ratio of stone aggregate and on the cement quantity in the grout; therefore, the stone aggregate particles remain in close contact before and after grouting. The only settlement that occurs is in the grout with respect to stone aggregate particles. In the examination, failed specimens showed greater loss of bond at the underside of the aggregates than at the top surfaces. This was due to the settlement of grout and to the bleeding of water that became trapped on the underside of stone aggregate particles, leaving a relatively weak zone [3]. Overdosing of cement can lower the concrete strength ($\bar{f}_c$) at c/s ratio = 1/0.8 and w/c ratio = 0.55 (Fig. 2), although it increases the strength of the grout itself. This can be explained by two factors: water quantity increase and shrinkage occurring mainly at the point of contact between the grout and stones [4].

At w/c ratio = 0.40 and c/s ratio = 1/1.5 for concrete with all kinds of stone aggregate the grout is too thick and not sufficiently liquid, the compressive strength ($\bar{f}_c$) will be less, and because the grout did not penetrate to all the voids in the stone aggregate, the matrix will be honeycombed

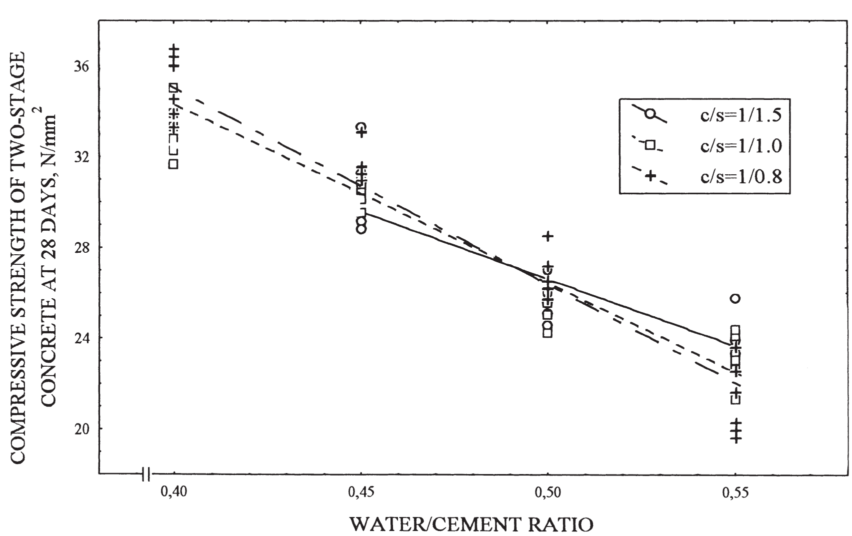

Fig. 2. Relation of compressive strength of two-stage concrete, water/cement ratio and cement/sand (c/s) ratio.

Table 5
Regression constants of $\bar{f}_c$ Eq. (5)

Kind of stone aggregate	No. of readings	a	b	d	e	Coefficient of correlation
Rounded	197*	63.43	−75.25	−0.06	0.21	0.952
Crushed	197*	61.24	−71.00	0.52	0.21	0.952
Mixed	197*	64.26	−75.33	0.26	0.13	0.948

* Does not include w/c ratio = 0.40 at c/s ratio = 1/1.5 in the general Eq. (5).

Table 6
Regression constants of $\bar{f}_c$ Eq. (6)

Kind of stone aggregate	β_0	β_1	β_2	Coefficient of correlation
Rounded	9.56	0.14	1.32	0.962
Crushed	6.70	0.42	1.07	0.969
Mixed	7.37	0.32	1.14	0.965

Does not include w/c ratio = 0.40 at c/s ratio = 1/1.5 in the general Eq. (6).

(Fig. 1). It does not include w/c ratio = 0.40 at c/s ratio = 1/1.5 in the general equation. For compressive strength of two-stage concrete an empirical general equation was calculated as given in Eq. (5):

$$\bar{f}_c = \gamma_0 + \gamma_1 * (w/c) + \gamma_2 * (c/s) + \gamma_3 * \text{time} \quad (N/mm^2) \tag{5}$$

where $\bar{f}_c$ = compressive strength of two-stage concrete (N/mm^2), and $\gamma_0, \ldots, \gamma_3$ are constants obtained from regression analysis and are given in Table 5.

3.5. Influence of compressive strength ($\bar{f}_g$) on compressive strength ($\bar{f}_c$)

The coefficient of w/c ratio is a fairly essential factor for characterizing grout. The influence of w/c ratio (at the same time of grout mixing) on two-stage concrete ($\bar{f}_c$) is different than in the case of traditional concretes. The strength of grout ($\bar{f}_g$) depends on the intensity of mixing, quantity of cement, w/c ratio, and consistency. Indirectly, the strength of concrete ($\bar{f}_c$) depends on the same factors, but to a smaller extent. The strength of concrete is not directly proportional to the strength of grout. This dependence for three kinds of stone aggregate is shown in Fig. 3. As can be seen, an 80% increase in strength of grout causes a mere 60–65% increase in concrete strength for rounded, crushed, and mixed stone aggregate, respectively (Fig. 3). This phenomenon can be explained by the fact that, because of point contact of stone aggregate grains in concrete, there is rather rigid stone aggregate that transfers at once the compressive stress without the grout. The strength of concrete depends first on tensile stress, mainly tearing the grains of aggregate from grout. This dependence can be shown by Eq. 6:

$$\bar{f}_c = \beta_0 + \beta_1 * \bar{f}_g^{\beta_2} \quad (N/mm^2) \tag{6}$$

where $\bar{f}_g$ = compressive strength of grout at 28 days (N/mm^2); $\bar{f}_c$ = compressive strength of two-stage concrete at 28 days (N/mm^2); β_0, β_1, β_2 are constants obtained from regression analysis and are given in Table 6.

The validity of Eq. (6) is 29 N/mm^2 < $\bar{f}_g$ < 52 N/mm^2.

Eq. (6) allows evaluation of the concrete compressive strength ($\bar{f}_c$) on the basis of the known grout compressive strength ($\bar{f}_g$). The samples of grout are easier to make and test than the samples of concrete, which must be large (at least 300 × 300 × 300 mm).

4. Algorithm for designing two-stage concrete

After analysis of the previously elaborated and listed equations, it was found that $\bar{f}_c$ = f(w/c ratio, c/s ratio, time of mixing, sedimentation, fluidity, and kind of stone aggregate).

It is not possible to formulate only one equation or function for designing the compressive strength of two-stage

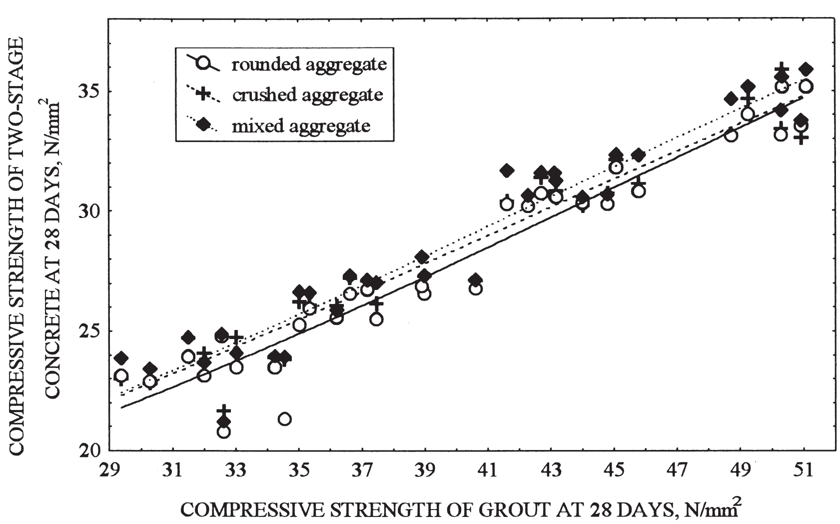

Fig. 3. Relation between compressive strength ($\bar{f}_c$) and compressive strength ($\bar{f}_g$) at 28 days for rounded, crushed, and mixed aggregates.

concrete ($\bar{f}_c$), but it is possible to describe an algorithm for designing the ($\bar{f}_c$), within the tested ranges as follows.

4.1. Design steps

1. Selection of available stones (rounded, crushed, or mixed) and the optimum value of duration of mixing = 4 min.
2. Estimate the average design compressive strength of two-stage concrete ($\bar{f}_c$) at 28 days.
3. From the average design strength ($\bar{f}_c$) we find out the compressive strength of grout ($\bar{f}_g$) from modified Eq. (6), and obtain Eq. (7):

$$\bar{f}_g = \sqrt[\beta_2]{\frac{\bar{f}_c - \beta_0}{\beta_1}} \quad (\mathrm{N/mm^2}). \tag{7}$$

4. General Eq. (4) for ($\bar{f}_g$) at 28 days:

$\bar{f}_g = \alpha_0 + \alpha_1 * (w/c) + \alpha_2 * (c/s) + \alpha_3 * \text{time}$ $(\mathrm{N/mm^2})$.

5. General Eq. (5) for ($\bar{f}_c$) at 28 days:

$\bar{f}_g = \gamma_0 + \gamma_1 * (w/c) + \gamma_2 * (c/s) + \gamma_3 * \text{time}$ $(\mathrm{N/mm^2})$.

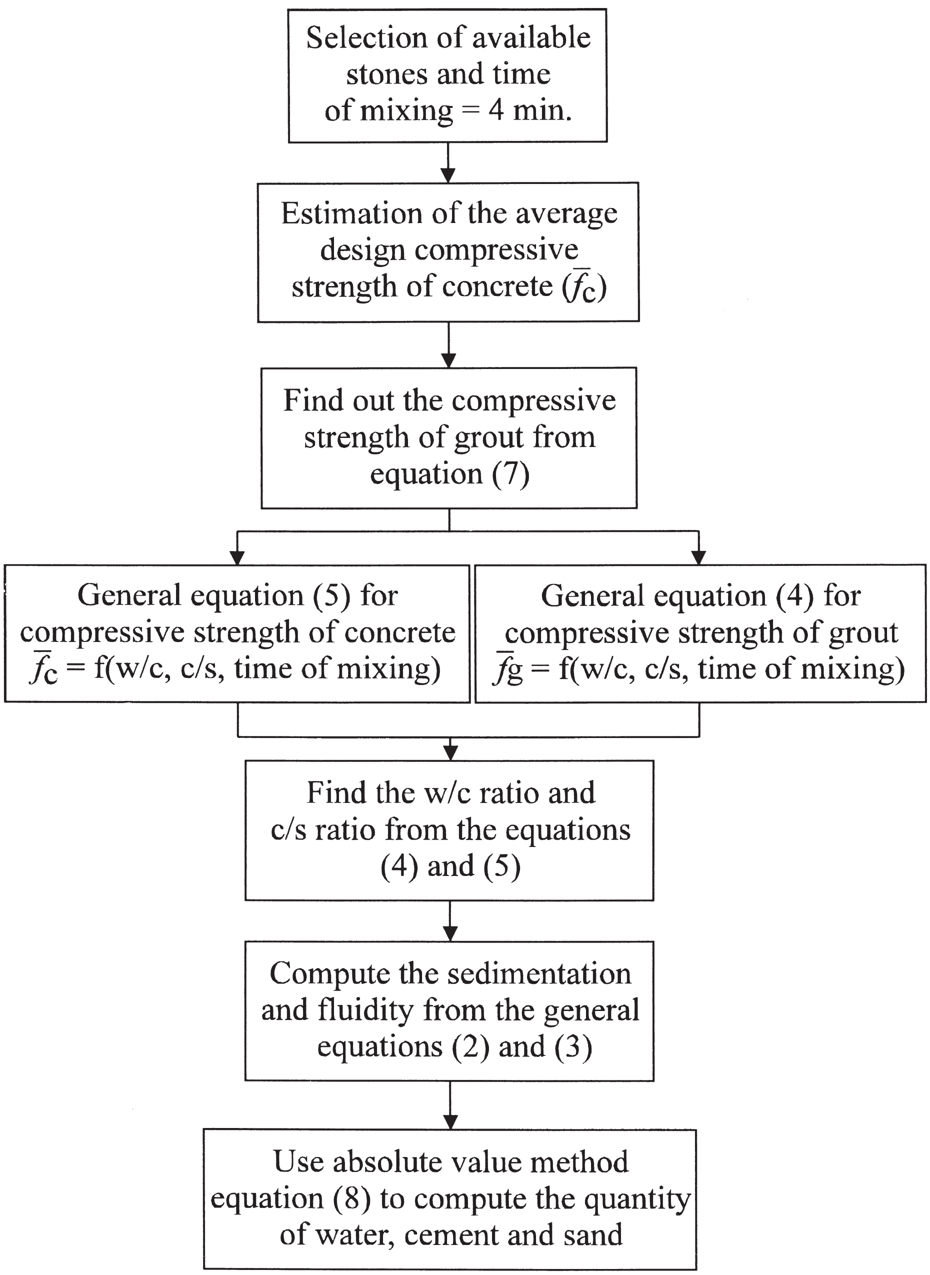

Fig. 4. Flow chart of the design steps.

6. Find the w/c ratio and c/s ratio from Eqs. (4) and (5).
7. Compute sedimentation from the general Eq. (2).
8. Compute the fluidity from the general Eq. (3).
9. Given the w/c ratio and c/s ratio, the mix proportions of grout are worked out using the absolute volume method given in Eq. (8):

$$\text{Volume of grout} = \mathbf{e}$$

$$W + \frac{C}{\rho_c} + \frac{S}{\rho_s} = \mathbf{e} * 1000 \quad (8)$$

where **e** = void ratio of kind of stone aggregate (rounded, crushed, or mixed); W = weight of water in kg/m^3 of concrete; C = weight of cement in kg/m^3 of concrete; S = weight of sand in kg/m^3 of concrete; ρ_c = specific gravity of cement = 3.10; and ρ_s = specific gravity of sand = 2.65.

4.2. Numerical example

1. Average design compressive strength $\bar{f}_c$ = 30 N/mm^2, optimum time of mixing = 4 min, and selected rounded stone aggregate.
2. Computed compressive strength of grout from Eq. (7):

$$\bar{f}_g = \sqrt[\beta_2]{\frac{\bar{f}_c - \beta_0}{\beta_1}} = \sqrt[1.32]{\frac{30 - 9.56}{0.14}} = 43.62 \text{ N/mm}^2.$$

3. From the general Eq. (4) and (5):

$$30 = 63.43 - 75.25 * (w/c) - 0.06 * (c/s) + 0.21 * 4$$

$$43.62 = 90.88 - 117.97 * (w/c) + 3.56 * (c/s) + 0.61 * 4.$$

4. Computed w/c ratio = 0.45 and c/s ratio = 1.1 from Eqs. (4) and (5).
5. Sedimentation = 2.16% from the general Eq. (2).
6. Fluidity = 91.8 mm from the general Eq. (3).
7. Using absolute volume method in Eq. (8):

$$W + \frac{C}{\rho_c} + \frac{S}{\rho_s} = \mathbf{e} * 1000$$

where **e** = void ratio of rounded stone aggregate = 39%

$$0.45 * C + \frac{C}{3.1} + \frac{C}{1.12 * 2.65} = \frac{39}{100} * 1000$$

The quantities of constituent materials per m^3 of concrete are cement (C) = 349.58 kg, sand (S) = 317.80 kg, and water (W) = 157.31 kg.

The values of compressive strength obtained from tests are compared with the computed compressive strength values and good agreement is obtained between the computed and experimental values. Similarly, the computed values of sedimentation and fluidity were nearly the same as the experimental values.

5. Conclusions

1. The results of testing grout properties and two-stage concrete changes at different activation times showed the optimum effects were obtained for 4 min of mixing. For this amount of mixing, the grout was characterized by little sedimentation, good fluidity, and high strength ($\bar{f}_g$).
2. The excess or deficiency of fine aggregate should not influence the mechanical parameters of the concrete (in the tested cement/sand range), but the change in sand quantity results in changes of the physical properties of the grout (e.g., fluidity and sedimentation).
3. At w/c ratio = 0.40 and c/s ratio = 1/1.5, the grout is too thick and will not penetrate all the voids in the stone aggregate, so the concrete will be honeycombed. A w/c ratio ≥0.45 in the case of c/s ratio = 1/1.5 will provide a grout with the necessary penetration.
4. There were three different stone aggregates used: rounded, crushed, and mixed. The best results were obtained for mixed aggregates, for all different grouts, because the mixed aggregate produced more contact points between grains of the aggregate than crushed and rounded aggregates.
5. An important feature observed in the two-stage concrete was its failure by cracking through the stone aggregate particles.

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