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# A new method for the mix design of medium strength flowing concrete with low cement content

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**Abstract**

The market for medium strength (28–35 MPa) concrete with high workability is recently increasing due to its qualitative and cost-saving advantages. This paper proposes a new mix design method for medium strength flowing concrete (FC) with low cement content. The proposed method determines the packing factor (aggregate content) first, and then fills binding paste containing fly ash and GGBS into the voids between aggregates to make concrete that has the desired workability and strength. Tests on slump, slump flow, and compressive strength were carried out and the results indicate that medium strength FC can be produced successfully using this method. Concrete mixtures designed by using the proposed method requires a small quantity of binder and is therefore very economical.



*Keywords:* Flowing concrete; Mix design; Medium strength; Packing factor; Slump; Slump flow; Compressive strength; Fly ash; GGBS

## 1. Introduction

Concrete is the dominant construction material today with an annual worldwide production of over 4.5 billion metric tons [1]. However, traditional concrete with high water to cement ratio (water content) and low workability is difficult to place and less durable. Large amounts of labor and energy are required for the placing of such concrete. Quality problems such as honeycomb, bleeding, and segregation sometimes occur. To solve these problems, concretes with high workability and high durability, such as high-performance concrete (HPC) and self-compacting concrete have recently been developed with the aid of superplasticizer (SP), but these types of concrete are presently expensive and require intense quality control [2–6]. Pollution is another problem associated with current concrete mixes. Harmful gases such as $CO_2$, $SO_2$, $NO_2$ and mill dusts are discharged into the atmosphere during the production of cement. The energy content of cement and aggregate are about 1300 and 8 kW h/t [1]. It is therefore important to reduce the cement content of concrete through proper mix proportions using industrial by-products such as fly ash (FA) and ground granulated blast-furnace slag (GGBS), efficiently contributing to global sustainable development [7,8]. Hence, medium strength flowing concrete (FC) or high workability concrete with a low cement content and a high content of cement replacement materials such as FA and GGBS would be an economical way to produce durable concrete.

Mix design methods such as those proposed by the ACI committee [9] for normal strength concrete are not suitable for proportioning concrete with high workability [10]. Many mix design methods based on different assumptions for high workable concrete like HPC have been proposed by Metha and Aitcin [2], the Laboratoire Central des Ponts et Chaussees (LCPC) [11], the Swedish Cement and Concrete Research Institute (CBI) [12], and Bharatkumar et al. [13]. These methods have proven to be successful in their own fields of application, but they often lead to a high paste volume if applied to medium strength FC, and are then neither economical nor durable.

This paper proposes a mix design method for medium strength FC with low cement content. After presenting

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the general considerations, the mix proportion procedures will be developed, followed by sample calculations and validation experiments. Finally, the effects of different factors on the workability and the strength of the concrete will be discussed.

## 2. General considerations

Concrete can be considered as a two phases material: aggregates and binding paste. The purpose of concrete mix design is to find the optimum proportion of each ingredient to meet the client's requirements with regard to workability, strength, durability, cost, and ecology. For FC, the requirement on workability is often more difficult to meet than the need for strength. That's why the proposed method starts with aggregate content, the most important parameter for workability. The workability of concrete can be characterized by its packing factor, defined in this study as the mass ratio of aggregate at a tightly packed state to that at a loosely packed state.

As industrial by-products, FA and GGBS are abundant in most countries in the world and are proven to significantly improve the workability and durability of concrete in an economical and an ecological way [1,8]. Thus, large amounts of FA and GGBS will be used in the proposed method. Because the Pozzolanic reaction of FA and GGBS is much slower that the hydration of cement [1,8], their contribution to the compressive strength of concrete is secondary as compared to that of cement, especially at 28 days when compressive strength is specified for normal strength concrete. Therefore, the proposed method considers cement as the primary provider of the compressive strength of concrete while FA and GGBS provides its workability. Water will be added to the FA and GGBS until they are as fluid as the cement paste.

## 3. Procedures of the proposed method

The principal consideration of the proposed method is to fill optimum amounts of binding paste into voids of aggregate framework loosely piled to satisfy the required properties of concrete with regard to workability and strength. The compressive strength of concrete at 28 days will be provided by the water/cement ratio and the cement content while the fluidity of fresh concrete will be provided by the volume ratio of aggregate to binding paste and the SP dosage. The use of FA and GGBS is based on durability, ecological, and economic considerations. They will be used to improve the fluidity and anti-segregation capabilities, not the compressive strength. Water will be added to FA and GGBS until they are as fluid as the cement paste. With the proposed

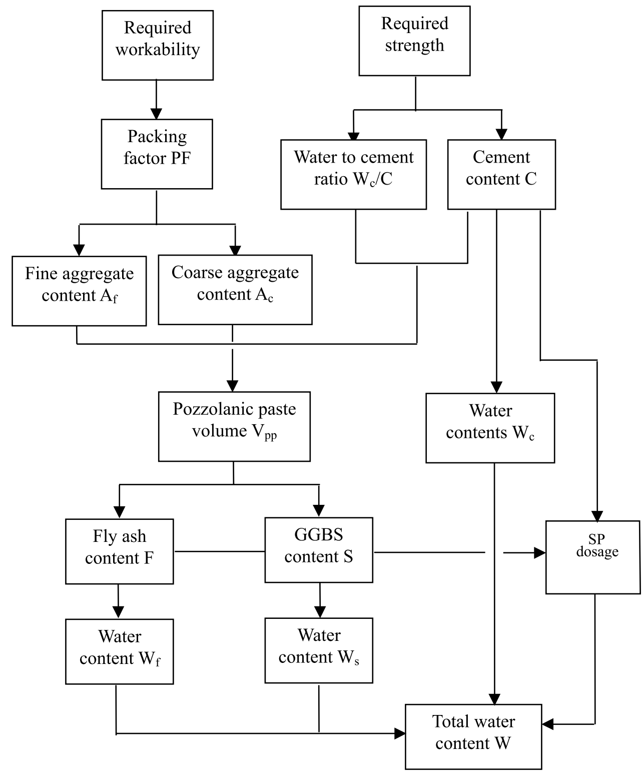


Fig. 1. Flowchart of the proposed mix design method.

method, all that needs to be done is to select the appropriate materials, do the calculations, conduct trial batches and make some adjustments, and FC of medium strength can be obtained. The flowchart of the proposed mix design method is presented in Fig. 1 and detailed procedures are summarized in the following steps.

*Step 1: Calculation of coarse and fine aggregate contents*

A higher PF value would imply a greater amount of coarse and fine aggregates used, thus decreasing the content of binding paste in FC. Consequently, its fluidity will be reduced. On the other hand, a low PF value would mean increased fluidity of concrete for the same consistency of binding paste. Therefore, it is important to select the optimal PF value to meet the required properties in mix design. The content of fine and coarse aggregates can be calculated as follows:

$$A_f = \mathrm{PF}\, A_{fo} \frac{V_{Af}}{V_A} \tag{1}$$

$$A_c = \mathrm{PF}\, A_{co} \left( \frac{1 - V_{Af}}{V_A} \right) \tag{2}$$

where $A_f$ is the content of fine aggregates, $A_c$ is the content of coarse aggregates, $A_{co}$ is the unit weight of loosely piled saturated surface-dry (SSD) coarse aggregate, $A_{fo}$ is the unit weight of loosely piled SSD fine aggregate, PF is the packing factor, the ratio of mass of aggregates in the mixture to that of loosely packed state according to ASTM C-29, 1.14–1.22 for FC [14], $V_{\mathrm{Af}}/V_{\mathrm{A}}$ is the volume ratio of fine aggregate to total aggregate.

*Step 2: Calculation of cement content*

Cement is regarded as the primary provider of the compressive strength of concrete. However, concrete with too much cement is neither economical nor durable. The proposed method suggests using minimum cement content for strength requirement. If a compressive strength of $x$ MPa at 28 d is expected for each kilogram of cement used, the cement content will be

$$C = \frac{f'_{\mathrm{c}}}{x} \tag{3}$$

where $C$ is the cement content (kg/m$^3$), $f'_{\mathrm{c}}$ is the specified compressive strength of concrete at 28 days (MPa), $x$ is the compressive strength provided by each kilogram of cement, in MPa, 0.11–0.14 MPa (15–20 psi) for FC used in Taiwan [14].

*Step 3: Selection of water/cement ratio*

The "required average compressive strength $f'_{\mathrm{cr}}$" must first be determined from the specified strength $f'_{\mathrm{c}}$ and variation on concrete strength during the production in the ready-mixed concrete plant. This can be done according to the method suggested by ACI 319-95 [15] as follows:

$$f'_{\mathrm{cr}} = \max(f'_{\mathrm{c}} + 1.34S, f'_{\mathrm{c}} + 2.33S - 35)\ (\mathrm{MPa}) \tag{4}$$

where $S$ is the standard deviation (MPa).

The relationship between $f'_{\mathrm{cr}}$ at 28 d and water/cement ratio for FC was obtained from previous experiments [16] and is presented on Fig. 2; this relationship is similar to that proposed by ACI 211.1 [9]. However, the selected water/cement ratio must satisfy both the strength and the durability criteria. Due to the lack of data on the durability of FC, the values can be taken from ACI 211.1 [9] in this study.

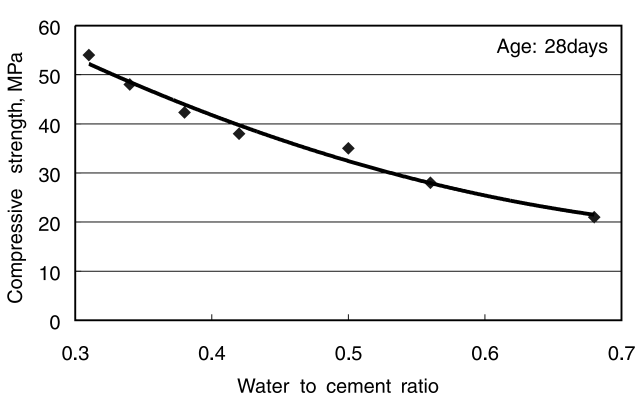


Fig. 2. Relation between compressive strength and water to cement ratio.

*Step 4: Calculation of mixing water content required by cement*

The content of mixing water required by cement can then be obtained using

$$W_{\mathrm{c}} = \left(\frac{W_{\mathrm{c}}}{C}\right)C \tag{5}$$

where $W_{\mathrm{c}}$ is the content of mixing water required by cement (kg/m$^3$), $W_{\mathrm{c}}/C$ is the water to cement ratio by weight.

*Step 5: Calculation of FA and GGBS contents*

To obtain the required workability and segregation resistance, FA and GGBS are used to increase the binder content. Then the paste volume of Pozzolanic materials ($V_{\mathrm{pp}}$) can be calculated as follows:

$$V_{\mathrm{pp}} = 1 - \frac{A_{\mathrm{co}}}{(1000G_{\mathrm{Ac}})} - \frac{A_{\mathrm{fo}}}{(1000G_{\mathrm{Af}})} - \frac{C}{(1000G_{\mathrm{c}})} - \frac{W_{\mathrm{c}}}{(1000G_{\mathrm{w}})} - V_{\mathrm{a}} - n\frac{(C+P)}{(1000G_{\mathrm{sp}})} \tag{6}$$

where $V_{\mathrm{pp}}$ is the volume of FA and GGBS paste, $G_{\mathrm{Ac}}$ is the specific gravity of coarse aggregates, $G_{\mathrm{Af}}$ is the specific gravity of fine aggregates, $G_{\mathrm{c}}$ is the specific gravity of cement, $G_{\mathrm{w}}$ is the specific gravity of water, $G_{\mathrm{sp}}$ is the specific gravity of superplasticizer (liquid), $V_{\mathrm{a}}$ is the air content (%), $P$ is the amount of FA and GGBS (kg/m$^3$), $n$ is the dosage of SP based on binder content (%).

In order to get the FA and GGBS paste with water/binder ratio of $W_{\mathrm{f}}/F$ and $W_{\mathrm{s}}/S$ as flowable as the cement paste, flow tests (ASTM C230) should be carried out. If the total amount of pozzolan materials (FA and GGBS) in FC is $P$, where FA occupies $A\%$ and GGBS occupies $1-A\%$, the adequate ratio of these two materials can be established through testing or according to previous experience [16].

$$V_{\mathrm{pp}} = \left(1+\frac{W_{\mathrm{f}}}{F}\right)A\%\frac{P}{(1000G_{\mathrm{f}})} + \left(1+\frac{W_{\mathrm{s}}}{S}\right) \times (1-A\%)\frac{P}{(1000G_{\mathrm{s}})} \tag{7}$$

where $G_{\mathrm{f}}$, $G_{\mathrm{s}}$, $G_{\mathrm{c}}$, $W_{\mathrm{f}}/F$, $W_{\mathrm{s}}/S$ and $A\%$ can be obtained from tests.

Let Eq. (6) equals Eq. (7), the total amount of Pozzolanic materials $P$ in FC can be obtained. Hence, FA content ($F$) and GGBS content ($S$) can be calculated as follows:

$$F = A\%P \tag{8}$$

$$S = (1-A\%)P \tag{9}$$

Mixing water content required for FA paste

$$W_f = (W_f/F)F \quad (10)$$

Mixing water content required for GGBS paste

$$W_s = (W_s/S)S \quad (11)$$

*Step 6: Calculation of SP dosage*

The SP can be deduced from the dosage at the saturation point from previous tests as Fig. 3. If the dosage of SP used is $n$% of the binder (cementitious material), and the solid content of SP is $m$%, then the SP dosage ($W_{sp}$) by liquid can be obtained as follows:

$$SP = n(C + P) \quad (12)$$

*Step 7: Calculation of mixing water content needed in FC*

The water content required by FC is the total amount of water needed for cement, FA and GGBS minus that in SP. Therefore, it can be calculated as follows:

$$W = W_c + W_f + W_s - (1 - m)n(C + P) \quad (13)$$

Previous experiences have shown that a total water content of 168–181 kg/m$^3$ is suitable for FC [17].

*Step 8: Adjustments for aggregate moisture*

The mix proportions determined by steps 1–6 are therefore based on the SSD condition of aggregates. Mixing water content should be adjusted according to the moisture content of aggregates and the amount of SP at the ready-mixed concrete plant or construction site.

*Step 9: Trial batch adjustments*

Evaluation of the trial mixes should be based on the criteria of workability (slump and slump flow) and compressive strength. Accordingly, adjustments should be made on PF value, water to cement ratio, cement content, fine/coarse aggregate ratio, and SP dosage. When a mixture satisfying the desired criteria of workability and strength is obtained, the mix proportions of the laboratory-sized trial batch are scaled up for producing full-sized field batches.

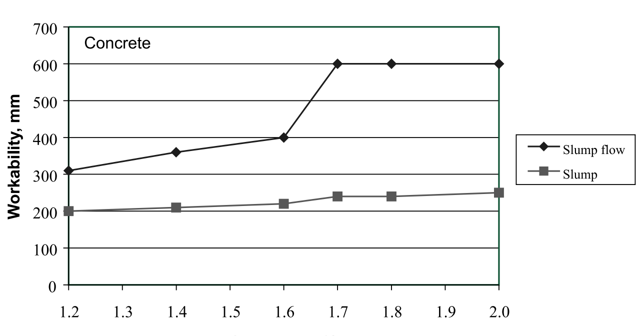


Fig. 3. Effect of SP dosage on the workability of concrete.

## 4. Sample computations

A concrete of 28 MPa with slump of $240 \pm 20$ mm and slump flow of $600 \pm 50$ mm were specified. Locally available Type I Portland cement, Class F FA, and GGBS with specific gravity of 3.15, 2.15, and 2.92 were used. Their physical properties and chemical compositions are shown in Table 1. The SP used was naphathalene-type with a solid content of 40% and specific gravity of 1.064. The coarse aggregate used was a crushed river gravel with a specific gravity of 2.66, maximum size of 25 mm and loose unit weight of 1581 kg/m$^3$ (ASTM C29). The fine aggregate was a river sand having a specific gravity of 2.63 at SSD condition, a fineness modulus of 3.2 and a loose unit weight of 1483 kg/m$^3$. Table 2 shows their gradations. The volume ratio of fine to coarse aggregate was chosen to be 52:48. The construction is a reinforced concrete footing continuously exposed to wet conditions but no freezing and thawing. Steps 1–7 compute the mix proportions with PF = 1.18 as follows:

*Step 1:* Assume PF = 1.18

$$\text{Fine aggregate content:} A_f = 1483 \times 1.18 \times 52\% = 910 \text{ kg/m}^3$$

$$\text{Coarse aggregate content:} A_c = 1581 \times 1.18 \times (1 - 0.52) = 896 \text{ kg/m}^3$$

*Step 2:* Each kilogram of cement is expected to provide 0.14 MPa compressive strength at 28 days [14].

$$\text{Cement content: } C = \frac{28}{0.14} = 200 \text{ kg/m}^3$$

*Step 3:* Assuming 3.5 MPa standard deviation from past experience, the required average strength ($f'_{cr}$) should be

$$f'_{cr} = \max(28 + 1.34 \times 3.5, 28 + 2.33 \times 3.5 - 3.5) = 32.7 \text{ MPa}$$

From Fig. 2, the water/cement ratio is 0.50 based on the required compressive strength of 32.7 MPa. The selected $W_c/C$ (=0.50) satisfies the durability criteria of ACI 211.1 for the given type of exposure conditions [9,16].

Table 1
Properties and compositions of cement, FA and GGBS

| Item | Materials | | |
|---|---|---|---|
| | Cement | FA | GGBS |
| *Physical properties* | | | |
| Fineness | | | |
| Amount retained on a 45 um sieve (%) | – | 15 | 9 |
| Blaine method ($cm^2/g$) | 3350 | – | 422 |
| Specific gravity | 3.14 | 2.10 | 2.93 |
| *Chemical composition* | | | |
| Loss on ignition (%) | 1.36 | 5.0 | 0.4 |
| $SiO_2$ (%) | 21.0 | 55.5 | 34.8 |
| $Al_2O_3$ (%) | 6.26 | 27.9 | 13.6 |
| $Fe_2O_3$ (%) | 3.09 | 6.3 | 0.32 |
| CaO (%) | 64.2 | 6.3 | 40.5 |
| MgO (%) | 1.53 | 1.6 | 6.96 |
| $SO_3$ (%) | 1.95 | 0.8 | 1.52 |
| Alkalinity (%) | – | 0.3 | 1.8 |
| Sulfide sulfur (%) | – | – | 0.5 |
| Free CaO | 1.36 | – | – |
| Insoluble residue (%) | 0.20 | – | – |
| $C_3S$ | 46.0 | – | – |
| $C_2S$ | 26.0 | – | – |
| $C_3A$ | 11.4 | – | – |
| $C_4AF$ | 9.4 | – | – |
| CSH | 4.73 | – | – |
| *Mortar* | | | |
| Air content of slag mortar (%) | | – | 3.5 |
| Slag activity index in 3 d (%) | | – | 72 |

Table 2
Gradations of aggregates (unit: % passing)

| Sieve size | Coarse aggregates | Fine aggregates |
|---|---|---|
| 1 in. | 100 | – |
| 3/4 in. | 87.1 | – |
| 1/2 in. | 38.4 | – |
| 3/8 in. | 25.8 | 100 |
| #4 | 0.95 | 98.9 |
| #8 | 0 | 89.1 |
| #16 | – | 66.5 |
| #30 | – | 41.0 |
| #50 | – | 20.3 |
| #100 | – | 6.7 |
| #200 | – | 2.4 |

*Step 4:* Mixing water amount for cement: $W_c = 0.50 \times 200 = 100\ \text{kg/m}^3$

*Step 5:* Entrapped air was estimated to be 1.8%. The optimum dosage of liquid SP equals 1.7% found from Fig. 3. The paste volume of Pozzolanic materials (FA and GGBS) can be expressed as follows:

$$V_{pp} = 1 - \left[\frac{910}{2660} + \frac{896}{2630} + \frac{200}{3150} + \frac{100}{10\,000} + 0.018 + \frac{0.017 \times (1-0.4) \times (200+P)}{1064}\right] \quad (14)$$

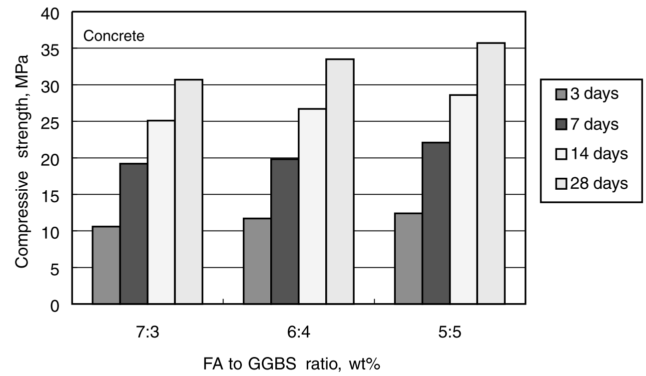


Fig. 4. Effect of FA to GGBS ratio on the compressive strength of concrete.

According to the flow table tests with the same dosage of SP, a water/binder ratio ($W_f/F$) of 0.52 for FA paste and of 0.42 ($W_s/S$) for GGBS paste were found to obtain the same flow value for the cement paste with $W_c/C = 0.50$. From Fig. 4, the optimum FA to GGBS (by weight) of 1:1 was obtained based on the compressive strength of concrete. The paste volume of Pozzolanic materials is

$$V_{pp} = (1+0.52)0.5\frac{P}{2150} + (1+0.42)0.5\frac{P}{2920} \quad (15)$$

Let (14) equals (15), one gets the amount of Pozzolanic materials:

$P = 155\ \text{kg/m}^3$

Thus, the FA and GGBS content: $F = S = 0.5 \times 155 = 77.5\ \text{kg/m}^3$.

*Step 6:* Dosage of SP: $W_{sp} = 0.017(200 + 77.5 + 77.5) = 6.0\ \text{kg/m}^3$

*Step 7:* Mixing water content: $W = 100 + 40.3 + 32.6 - (1-0.4)6.0 = 169\ \text{kg/m}^3$

Mix proportions were also calculated for different PF values from 1.14 to 1.22 and presented in Table 3.

## 5. Experimental program

In order to verify the validity of the proposed mix design method, a set of FC mixes based on the above procedures was prepared. The properties of the raw materials used were described in the previous section. The slump and slump flow as well as the air content of fresh concrete were tested. Standard cylinders of $150 \times 300$ mm for compressive tests were prepared and cured in lime-saturated water until test ages. The procedures followed during those tests are listed in Table 4.

Table 3
Mix proportions of FC obtained with the proposed method (unit: kg/m$^3$)

| Packing factor | Coarse aggregates | Fine aggregates | Cement | FA | GGBS | Water | SP | Water/binder ratio |
|---|---|---|---|---|---|---|---|---|
| 1.14 | 865 | 879 | 200 | 89 | 89 | 180 | 6.4 | 0.476 |
| 1.16 | 880 | 895 | 200 | 83 | 83 | 174 | 6.2 | 0.475 |
| 1.17 | 888 | 902 | 200 | 79 | 79 | 171 | 6.1 | 0.478 |
| 1.18 | 895 | 910 | 200 | 76 | 76 | 168 | 6.0 | 0.477 |
| 1.19 | 903 | 918 | 200 | 73 | 73 | 165 | 5.9 | 0.477 |
| 1.20 | 911 | 925 | 200 | 69 | 69 | 162 | 5.8 | 0.479 |
| 1.22 | 926 | 941 | 200 | 63 | 63 | 156 | 5.5 | 0.479 |

Table 4
Test methods of concrete properties

| Item | Test method |
|---|---|
| Slump | ASTM C143 |
| Slump flow | JASS T-503[a] |
| Compressive strength | ASTM C39 |
| Air content | ASTM C231 |

[a] From Ref. [20].

## 6. Test results and discussion

### 6.1. Effect of PF on the workability of concrete

Table 3 shows that a reduction in PF value would decrease aggregate content, but increase the content of binding paste, thus enhancing slump and slump flow of FC. Fig. 5 shows that the volume of binding paste has a major effect on the slump and slump flow of concrete. $FC_S$ with good workability were obtained with a packing factor ranging from 1.16 to 1.20 which means a paste volume from 290 to 310 L/m$^3$ (Table 5). These results agree with those of Okamura [6,18] who suggested a paste volume of 295 L/m$^3$ or higher for self-compacting concrete. Mehta and Aitcin [2] suggested a paste volume of 350 L/m$^3$ for HPC with a slump of about 180–200 mm. From the same Figure, if the same slump was specified for a normal strength concrete, a paste volume as low as 290 L/m$^3$ would be enough. This agrees with that suggested by Wu and Lein [19].

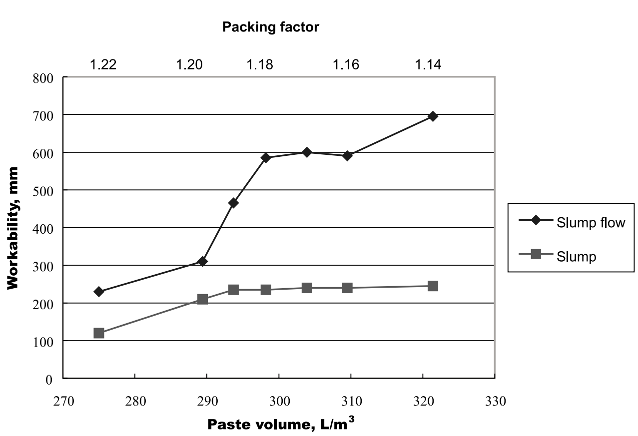


Fig. 5. Effect of paste volume on the workability of concrete.

When the ratio of slump to slump flow was 0.4 for PF = 1.16–1.18, the concrete had better consistency, plasticity, and flowability. The concrete became too sticky when PF $\geqslant$ 1.19 with a slump/slump flow ratio $\geqslant$ 0.5. In contrast, bleeding and segregation were observed on concrete with PF = 1.14 (slump/slump flow = 0.35) indicating that the paste volume was too high. In addition, when PF = 1.17, the loss in slump and in slump flow was very low: the slump and slump flow were 240 and 600 mm after mixing; 50 min later, they were 220 and 580 mm. The best results on workability and on slump loss were obtained with PF = 1.17. Regarding slump flow, a value of 600 $\pm$ 50 mm was obtained for PF ranging from 1.16–1.18 with a coarse aggregate content from 331–337 L/m$^3$ (Table 5). These results were within the range (300–360 L/m$^3$) suggested in reference [6] for self-compacting concrete with a 500–650 mm slump flow.

### 6.2. Effect of PF on the compressive strength of concrete

Fig. 6 shows the compressive strength of FC as affected by the PF value. The highest compressive strength was observed with PF = 1.17 at all concrete ages tested. As mentioned above, the best workability was obtained with PF = 1.17. When PF = 1.14, the compressive strength of concrete was 17–24% lower than that with PF = 1.17, probably because the concrete had large amount of paste and was bleeding slightly and segregated. Moreover, the compressive strength of FC with PF = 1.22 was 19–27% lower than that with PF = 1.17 probably due to the low workability which could make concrete more difficult to compact. At 28 d, the average compressive strength of concrete with PF = 1.17 was 7.2 MPa (27%) higher than the specified strength which is a reasonable margin for a ready-mixed concrete plant to overcome its strength variation during production.

Table 5
Volume proportions of materials in FC obtained with the proposed method (unit: L/m$^3$)

| Packing factor | Coarse aggregates | Fine aggregates | Cement | FA | GGBS | Water | SP | Paste |
|---|---|---|---|---|---|---|---|---|
| 1.14 | 325 | 334 | 63.5 | 41.5 | 30.5 | 180 | 6.0 | 321 |
| 1.16 | 331 | 340 | 63.5 | 38.4 | 28.3 | 174 | 5.8 | 310 |
| 1.17 | 334 | 343 | 63.5 | 36.8 | 27.1 | 171 | 5.7 | 304 |
| 1.18 | 337 | 346 | 63.5 | 35.3 | 26.0 | 168 | 5.6 | 298 |
| 1.19 | 340 | 349 | 63.5 | 33.8 | 24.9 | 165 | 5.5 | 294 |
| 1.20 | 342 | 352 | 63.5 | 32.2 | 23.7 | 162 | 5.4 | 290 |
| 1.22 | 348 | 358 | 63.5 | 29.2 | 21.5 | 156 | 5.2 | 275 |

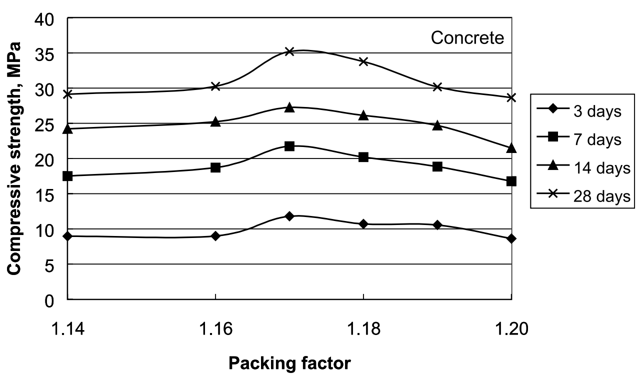


Fig. 6. Effect of packing factor on the compressive strength of concrete.

### 6.3. Air content

The air content of fresh concrete in this study ranged from 1.6 to 2.0%, a percentage which approaches the assumption of 1.8% used in the sample calculations.

### 6.4. Limitation on the proposed method

At the present state-of-the-art, successful fabrication of FC depends on a combination of empirical rules derived from experience, laboratory work and a great dose of common sense and observation. Applying step by step of the procedures of mix design method proposed in this paper should facilitate the selection of proportions that will result in medium strength FC that is workable, strong and economical. In general, the calculated proportions should provide a mix having almost the desired characteristics. However, if the cement, FA, or GGBS are not suitable, if the grading of aggregates is not good enough, if the SP is not efficient enough, if the selected binder/SP combination is not fully compatible or some other unexpected factors intervene, the concrete may not reach the desired level of flowability. If the concrete does not have the desired slump flow and slump, either the PF value should be decreased or the SP dosage increased, or else the water content has to be increased as well as the binder content to keep the same water/binder ratio. The workability of the mix may be inadequate due to a poor shape or gradation of the coarse aggregate, or the incompatibility of the particular binder/SP combination. In the first case, the PF value has to be decreased, and in the second case, the fly ash, GGBS, or the SP should be changed. If fresh concrete bleeds or segregates, the amount of water, fine aggregate, SP dosage or type, and FA content should be adjusted. However, improvements to these proposed calculations could always be made.

A local ready-mixed concrete plant has produced FC following the proposed mix design method. Medium strength concretes with high workability, low cost and reliable quality were obtained. The results will be presented in a later publication.

## 7. Conclusions

Based on the results of this study, the following conclusions can be drawn:

1. Medium strength FC can be obtained using the proposed mix design method with cement content of as low as 200 kg/m$^3$.
2. The aggregate packing factor determines the aggregate content and influences the workability and strength of concrete.
3. FC designed with the proposed mix design method contains more aggregate but less binder, thus enhancing the economical and ecological advantages.
4. According to the proposed method, medium strength FC can be produced with a paste volume of 290–320 L/m$^3$ with the raw material used.
5. The water content of FC prepared by the proposed method is about 168–180 kg/m$^3$.
6. Concrete mixtures designed by using the proposed method requires a small quantity of binder (about 370 kg/m$^3$) and is therefore very economical.
7. The PF value is the controlling factor in the workability of concrete. A PF value of 1.16–1.18 is suggested.

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## References

[1] Mehta PK. Concrete: structure, properties, and materials. New Jersey: Prince-Hall Inc.; 1986.
[2] Mehta PK, Aitcin PC. Principles underlying production of high-performance concrete. Cement Concrete Aggreg 1990;12(2):70–8.
[3] Shah SP. High-performance concrete: past, present and future. In: Proceedings of the International Symposium on High Performance Concrete, The Hong Kong University of Science and Technology, China. 2000. p. 3–29.
[4] Aitcin PC. High-Performance Concrete. London: E & FN SPON; 1998.
[5] Henry GR. ACI define high-performance concrete. Concrete Int 1999;21(2):56–7.
[6] Okamura H. Self-compacting high-performance concrete in Japanese Tokyo: Social System Institute; 1999.
[7] Mehta PK. Role of Pozzolanic and cementitious material in sustainable development of the concrete industry. ACI SP 1998; 178:1–20.
[8] Neville AM. Properties of concrete. 4th ed. England: Longman House; 1995.
[9] ACI Standard 211.1, Standard practice for selecting proportions for normal, heavyweight, and mass concrete. ACI Manual of Concrete Practice, Part 1. 1996. p. 211.1-1–38.
[10] PCA, Design and Control of Concrete Mixtures. Portland Cement Association, Skokie, 6th ed. 1995. p. 79–94.
[11] de Larrard F. Concrete mixture-proportioning a scientific approach. In: Modern Concrete Technology Series, vol. 9. London: E & FN SPON; 1999. p. 421.
[12] Chai HW. Design and testing of self-compacting concrete. Ph.D. Thesis. University of London, London, 1998.
[13] Bharatkumar BH, Narayanan R, Raghuprasad BK, Ramachandramurthy DS. Mix proportion of high-performance concrete. Cement Concrete Compos 2001;23:71–80.
[14] Su N, Hsu KC, Chai HW. A simple mix design method for self-compacting concrete. Cement Concrete Res 2001;31:1799–807.
[15] ACI Committee 318, Building Code Requirements for Reinforced Concrete. Building Code Commentary, ACI 318R, 1995.
[16] Kao CC, Hsu KC, Su N. Effects of superplasticizer and Pozzolanic materials on properties of medium strength high-performance concrete. Taipei: Chinese Society of Structural Engineering; 1999.
[17] Hon NC. In: Flowing concrete. Beijing, China: China Railway Pub; 1988. p. 146–82.
[18] Okamura H. Self-compacting high-performance concrete. Concrete Int. 1997;19(7):50–4.
[19] Wu CW, Lein FJ. In: High-performance concrete. Beijing: China Railway Pub; 1999. p. 179.
[20] JASS T-503, Recommendations for Mix Design and Construction Practice of High Fluidity Concrete. Japanese Architecture Society, Tokyo: Gihoudou Pub.; 1997.