Optimum Mix Proportions for Flowing Concrete

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The optimum mix proportions for flowing concrete were investigated statistically by examining the effects of cement, water, fine aggregate, and superplasticizer on the properties of concrete. The properties considered were slump, slump flow, DIN flow, three kinds of workability, air content, segregation, bleeding, compressive strength, tensile strength, Young's modulus, drying shrinkage, moisture loss, crack, and cost. It was shown that these can be controlled by varying the level of each factor. The above characteristic properties were combined into three parameters indicating flowability, physical properties of hardened concrete, and workability. By using these parameters, the flowing concrete was classified into three categories: mixes exhibiting excellent properties in all respects and suitable for commodity-type high-grade concrete, mixes giving hardened concrete with excellent properties and suitable for reduced-crack or water-tight concrete, and mixes having improved flowability and workability and suitable for extensively steel-reinforced buildings. The optimum mix proportions for these uses have been demonstrated to be achievable.

The "Fliessbeton" or flowing concrete technology developed in West Germany a few years ago has been in practical use in Japan since 1975; 900 000 m³ of flowing concrete have been placed since then. However, little has been reported on the mix proportioning of flowing concrete, and most of the mix proportions now being used are determined from preliminary tests on dosages for conventional high-slump concrete, which do not always meet the requirements for optimum properties.

In this investigation, the optimum mix proportioning for flowing concrete for general building construction was investigated by statistical analysis of the interrelations between the mix proportions of flowing concrete prepared with naphthalene superplasticizer and its characteristic properties, including those of hardened concrete.

METHOD

Materials

Onoda ordinary portland cement was used, and the fine aggregate was Kinokawa river sand [ρ (specific gravity) = 2.58, fineness modulus (FM) = 2.91]; the coarse aggregate was crushed stone from Takarazuka combined with gravel from Hidaka-gawa River (ρ = 2.62, FM = 6.76). The admixture for the base concrete was a commercial air-entraining agent, while the superplasticizer was Mighty FD naphthalene, manufactured by the Kao Company.

Procedure

The scheme for the optimum mix proportioning is given in Figure 1. The variable factors, mix conditions, and the characteristic properties of concrete are summarized in Table 1. Four factors varied at five levels were allocated in an orthogonal matrix. Fifty batches of fresh concrete were mixed with the 25 kinds of mix proportions, and 15 properties were determined for each mix. The variation range of the level for each factor was determined by referring to the practical construction data. Those properties with no standard for testing were determined by the following methods.

Workability

According to Fukuchi (1), a specially designed test apparatus was employed. The box test apparatus is equipped with a vertical half plate that separates the upper room of the box so that the fresh concrete entering from one opening can flow to another through the bottom opening. The box is mounted on a flow table. By using the apparatus it was possible to determine the workability, the mobility of concrete at placing, the flow rate on vibration, and the number of vibrations required to complete compaction.

The degree of separation of aggregate was determined from the weight ratio of segregated coarse aggregate to the placed concrete, and the rate of crack formation expressed in days was determined by observation of the outset of crack formation onto the stressed specimen.

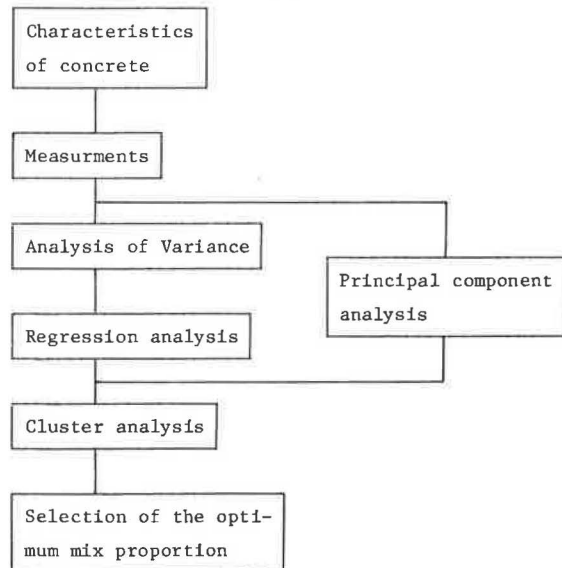Figure 1. Scheme for selecting optimum mix proportioning.

Table 1. Summary of experiment.

Factor	Level				
	-2	-1	0	1	2
Cement content (kg/m³)	280	290	300	310	320
Water content (kg/m³)	170	175	180	185	190
Sand (%)	42	44	46	48	50
Dosage of superplasticizer (%)	0.4	0.5	0.6	0.7	0.8

Table 2. Analysis of variance and analysis of principal components.

| Property | Analysis of Variance | | | | | | Analysis of Principal Components | | | |
| | Rate of Contribution[a] | | | | | | Factor Loading | | | |
	C	W	S	SP	Interaction	Total	Z1	Z2	Z3	Contribution
Slump	-	23	-	23	-	46	0.90	-0.14	0.23	88.2
Slump flow	-	15	19	49	-	83	0.95	0.20	-0.05	95.1
DIN flow	-	11	11	56	-	78	0.94	0.09	-0.09	90.3
Workability 1	49	13	-	11	-	73	0.78	0.20	0.55	94.6
Workability 2	-	46	-	-	WxSP:14	60	0.62	-0.09	0.66	82.5
Workability 3	38	14	-	-	-	52	0.64	0.04	0.71	91.4
Air content	-	24	40	12	WxSP:8	84	-0.74	-0.17	0.51	84.3
Segregation	17	-	42	-	-	59	0.74	-0.22	-0.36	72.7
Bleeding	-	56	13	-	-	69	0.70	0.12	-0.60	86.4
Compressive	37	34	-	10	WxSP:5	86	-0.54	0.62	0.50	91.5
Tensile strength	29	8	32	-	CxW:8 CxSP:6	83	-0.02	0.89	0.05	79.9
Young's modulus	13	18	23	9	WxSP:12	75	-0.23	0.72	-0.15	60.0
Drying shrinkage	-	47	27	-	CxW:5 WxSP:3	82	-0.09	-0.76	0.13	60.0
Moisture loss	23	34	30	-	-	87	0.01	-0.94	-0.16	90.5
Crack	-	-	-	-	CxW:35	35	0.17	0.79	-0.31	74.6
Eigen value							5.96	3.98	2.47	
Cumulation							40	66	83	

[a] C = cement content; W = water content; S = percentage sand; SP = dosage of superplasticizer.

Table 3. Qualitative relations between mix proportions and characteristic properties of concrete.

| Property | Ingredient | | | |
	Cement	Water	Sand	Mighty FD
Slump	-	I	-	I
Slump flow	-	I	D	I
DIN flow	-	I	D	I
Workability 1	I	I	-	I
Workability 2	-	I	-	I
Workability 3	I	I	-	-
Air content	-	D	I	D
Segregation	D	-	D	-
Bleeding	-	-	D	-
Compressive strength	I	-	-	-
Tensile strength	I	D	D	-
Young's modulus	I	D	D	-
Drying shrinkage	-	I	I	-
Moisture loss	D	I	I	-
Crack	D	I	-	-
Parameter Z1	-	I	-	I
Parameter Z2	I	D	D	-
Parameter Z3	I	-	I	-

Note: I = increasing; D = decreasing.

DISCUSSION OF RESULTS

Statistical Test on the Effects of Variable Factors

The analysis of variance was made on the results of 15 properties. The effect of each factor was tested statistically. In Table 2 are shown the contributions of significant factors by F-test. From this table one can see that these factors greatly affected each property. The results also indicate that the properties of flowing concrete can be controlled by varying mix levels of cement, water, fine aggregate, and superplasticizer.

Determination of Response Function

The value of each characteristic property was approximated by using the following response function, where Xi (i = 1-4) denotes the level of each factor and where the first five terms are linear, the next four terms are quadratic, and the final six terms are interaction terms.

$$Y = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + a_4x_4$$
$$+ a_{11}x_1^2 + a_{22}x_2^2 + a_{33}x_3^2 + a_{44}x_4^2$$
$$+ a_{12}x_1x_2 + a_{13}x_1x_3 + a_{14}x_1x_4$$
$$+ a_{23}x_2x_3 + a_{24}x_2x_4 + a_{34}x_3x_4 \quad (1)$$

The qualitative relations among mix formulations and properties of concrete indicated by the response function are summarized in Table 3. For instance, increasing water or superplasticizer seems to increase the slump value. Also indicated is that drying shrinkage can be reduced by reserving water or fine aggregate. Generally, increasing cement or superplasticizer gives better results, whereas increasing water or fine aggregate does not always do so. Results differ depending on the property being considered.

Combined Parameters Summarizing Fifteen Properties

Because of the difficulty in grasping 15 characteristic values at once intuitively, these values have been combined into three values by using principal-component analysis. The results are shown in Table 2. The principal component Z1 interrelates significantly with slump, slump flow, and DIN flow values and is regarded as a combined characteristic parameter controlling the flow property of fresh concrete. The principal component Z2, on the contrary, relates to the moisture loss by drying and tensile strength and can be regarded as a combined characteristic parameter controlling the property of hardened concrete. Finally, the principal component Z3 relates to flowability -1, -2, and -3 and to the degree of segregation of aggregate and can be related as a combined parameter to the workability or ease of placement of fresh concrete. The sum of the contribution rates of the three principal components reaches 83 percent, which indicates that the 15 properties of flowing concrete can be summarized into three combined parameters that provide all but 17 percent of the needed information. Based on these results, the three parameters were employed as criteria for selecting the optimum proportion of flowing concrete.

Selection of the Optimum Mix Proportion

Mix proportions of 625 kinds allocated in four factors by five levels were made. The 15 characteristic properties were simulated by using the response function, from which the mix proportions with desirable properties were selected.

For the first step, the mix proportions that displayed a particular dominant character were selected. Figure 2 is an illustration of this type expressed in

chart form and showing the mix formulation and the corresponding characteristic values for the mix with high slump value. In this particular case, the advantage of higher flowability is cancelled out by the disadvantages of higher bleeding and aggregate segregation.

In the chart, the three combined parameters—Z1, Z2, and Z3—are shown in the inner circle, whereas the 15 characteristic properties and material costs of concrete are shown clockwise. The mix proportions are shown in the upper left of the chart.

Each characteristic property except mix formulation tends toward optimum as it extends to the outer circle.

The average value is shown by an intermediate circle. The spacing between circles represents a threefold standard deviation (3σ). The proportions of the triangle form a criterion for the total characterization of the flowing concrete.

Another example of mix proportion for high tensile strength is shown in Figure 3; an example of lower bleeding is shown in Figure 4. From Figures 2 to 4, it is obvious that, as a rule, the improvement of certain properties is counterbalanced by the worsening of others. Therefore, it is difficult to establish an ideal mix proportion that has excellent characteristics in all respects.

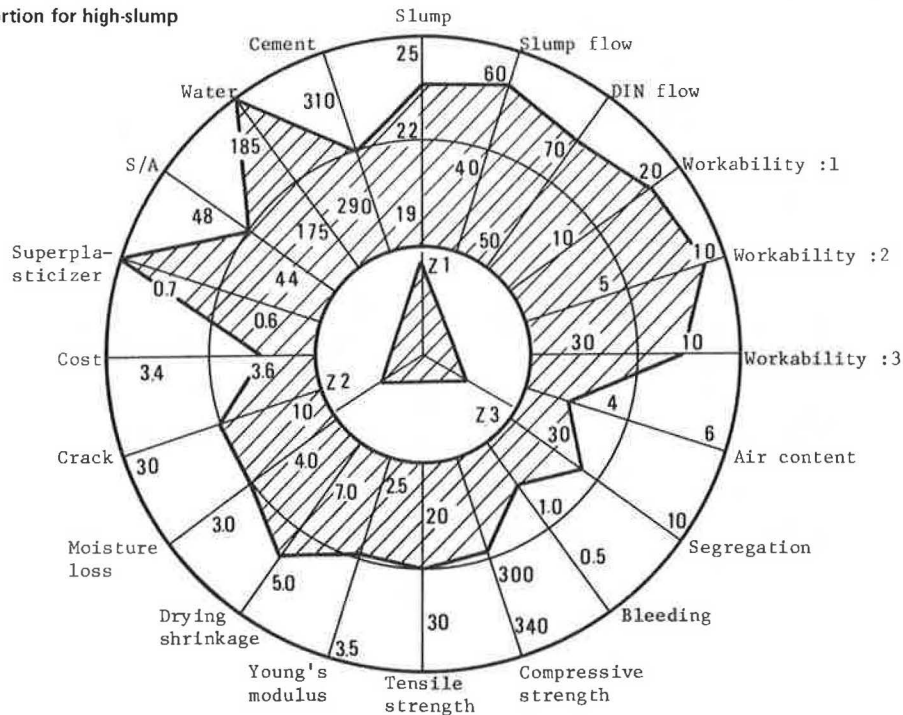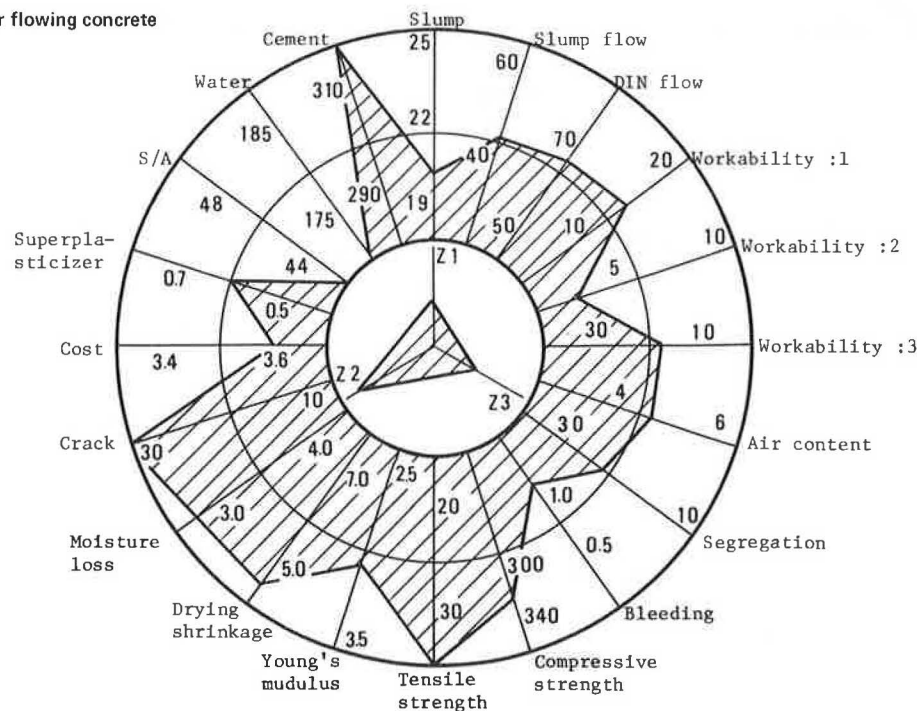Figure 2. Mix proportion for high-slump flowing concrete.

Figure 3. Mix proportion for flowing concrete of high tensile strength.

For the second step, the three combined parameters were taken into account to select the optimum mix proportion. In doing this, those mix proportions that had above-average parameter values (top 10 percent) were selected; thus, 65 mixes were selected out of 625. By further cluster analysis, these 65 mixes were classified into three categories: Those belonging to the first category exhibit excellent properties in all respects, a mix of the second category gives a hardened concrete with excellent properties, and a mix of the third category has an improved flowability and workability.

In Figures 5-7 are illustrated the typical patterns for each category. Of these, Figure 5 is an illustration for a mix that has outstanding performance and is above average in all respects and can be regarded as an example of the optimum mix proportion for high-grade ready-mixed concrete of commodity type. On the other hand, Figure 6 illustrates the mix proportion for hardened concrete with improved properties that is regarded as the most reasonable mix proportion for re-

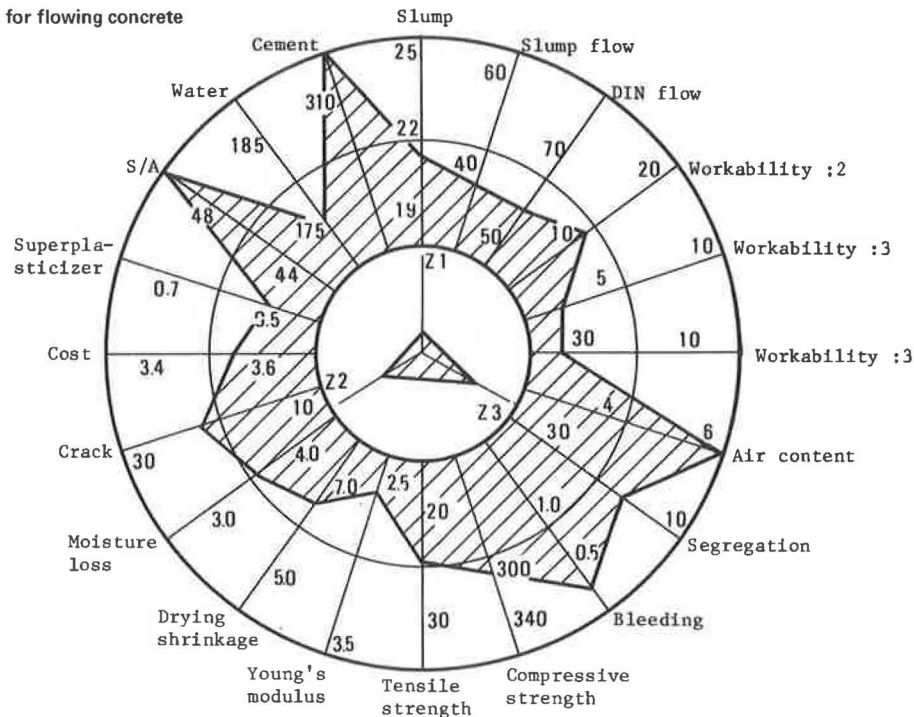Figure 4. Mix proportion for flowing concrete with lower bleeding.

Figure 5. Mix proportion for flowing concrete exhibiting excellent properties in all respects.
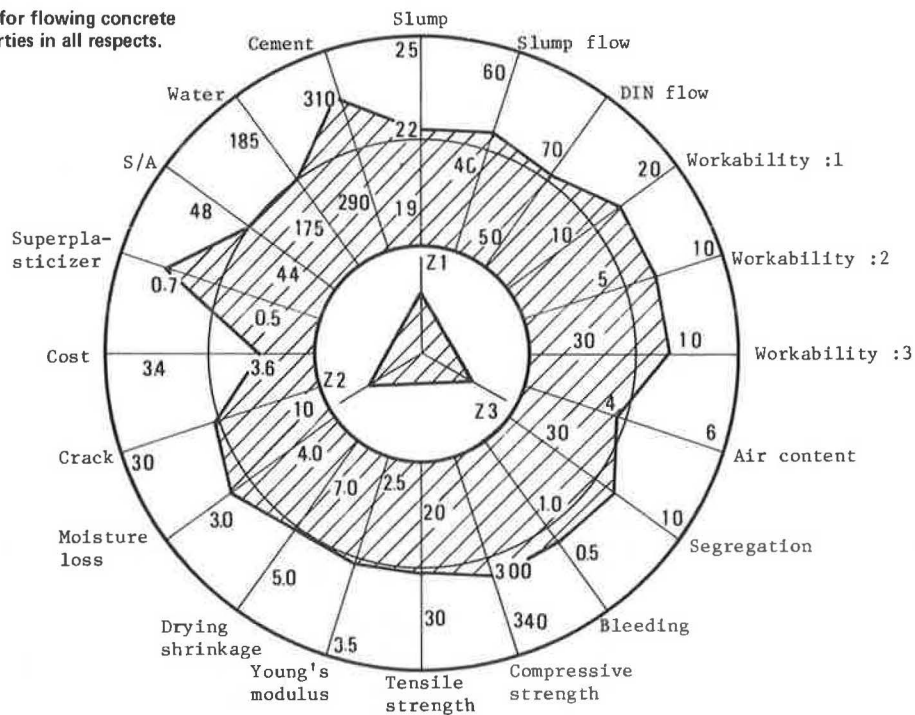
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Figure 6. Mix proportion for flowing concrete giving hardened concrete with excellent properties.
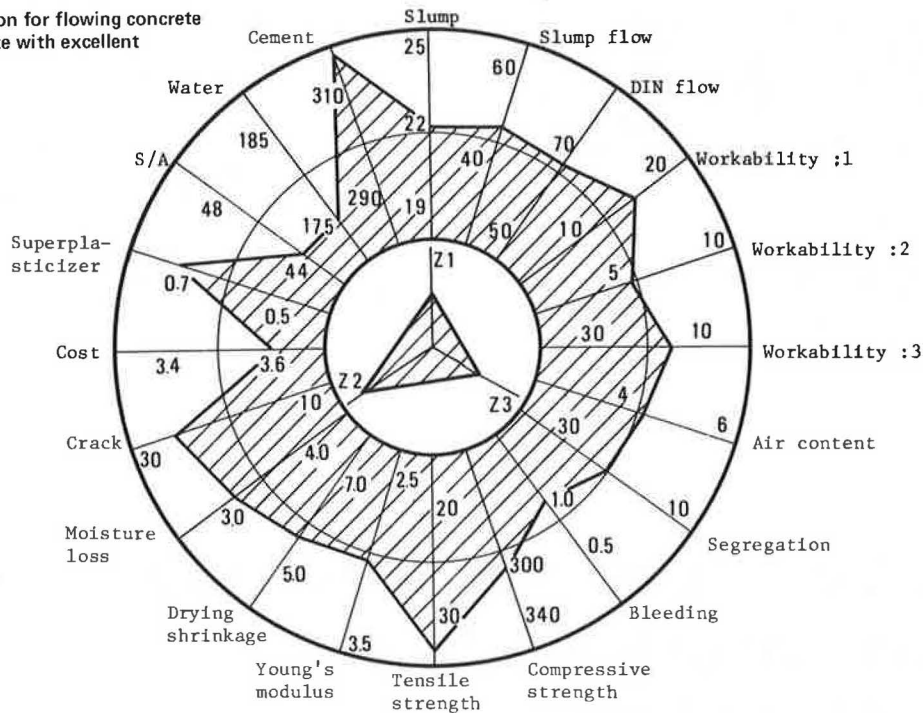

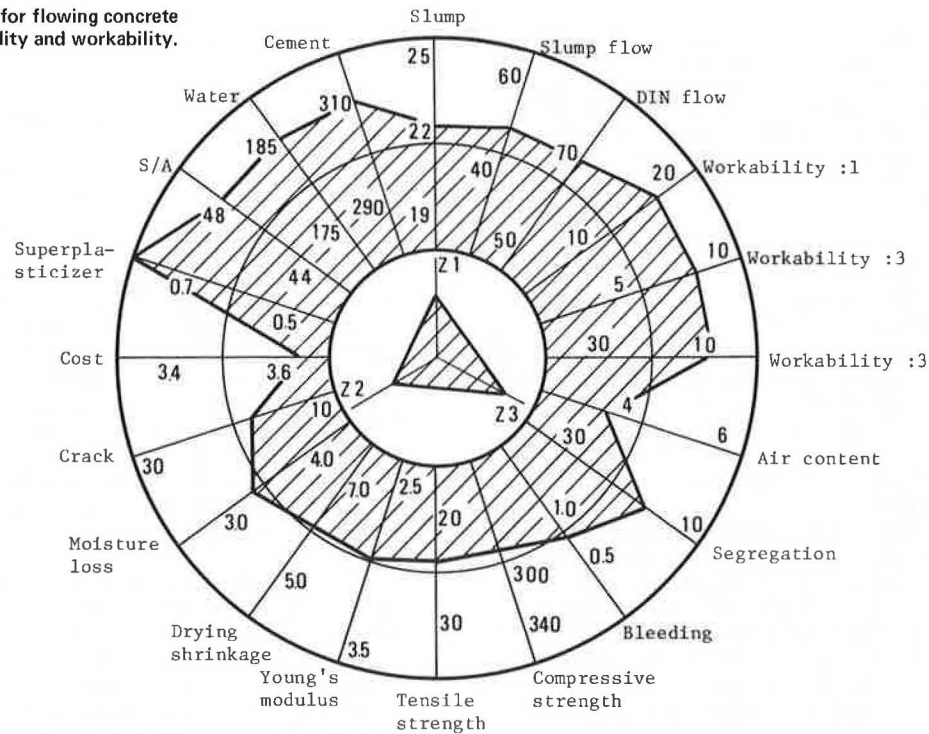Figure 7. Mix proportion for flowing concrete that has improved flowability and workability.

Table 4. Fundamental mix proportions of flowing concrete for various purposes.

Purpose	Base Concrete				Flowing Concrete		
	Slump (cm)	S/A (%)	Cement Content kg/m³	Base Admixture	Slump (cm)	Air Content (%)	Super-plasticizer (%)
High-grade ready-mixed concrete (above average in all properties)	12	46	300	AEA	22	4.0	0.6
Water-tight concrete with reduced cracking (good properties in hardened stage)	8	44	320	AEA or DA	21	3.5	0.7
Built-in tiling process, highly reinforced (good flowability and workability)	15	48	310	AEA	23	4.5	0.5

duced cracking and water-tight concrete. In contrast, Figure 7 is an example of the optimum mix proportion for improved flowability as well as workability; it is suitable for built-in tiling or highly steel-reinforced building structure. In Table 4 the fundamental mix proportions of flowing concrete for various purposes are summarized.

ACKNOWLEDGMENT

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Cement-Content Measurements with the Rapid-Analysis Machine

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The rapid-analysis machine (RAM) is a relatively new apparatus developed by the Cement and Concrete Association of England. RAM determines the cement content of fresh concrete by a wet-analysis process through a series of automatically controlled devices. This paper gives details of experience with this machine under controlled laboratory and normal field conditions. It was noted that the machine is capable of carrying out routine testing of fresh concrete efficiently under field conditions.

The traditional way of determining the satisfactory characteristics of concrete delivered to a site is to cast standard cylinders and to test these after curing at an age of 28 days. As techniques have advanced, certain accelerated test methods have come into vogue, and these enable the quality of the concrete to be predicted by tests at ages of only one or two days. However, even a day after a faulty concrete has been placed in a structure, the concrete has set, is hard, and will be expensive to replace.

Recognition of the advantages of being able to determine properties of the plastic concrete before it is placed into the structure is therefore growing. The rapid-analysis machine (RAM), although it does not produce all the required answers, does determine one of the critical characteristics of the concrete mix: its cement content. By using the equipment now available it is possible to make the test within 5 min of taking a sample.

OBJECTIVE

In addition to a brief description of RAM, the objective of this paper is to describe our experience with using this machine on concretes mixed under the various conditions below:

1. In the laboratory,
2. Ready mixed in a few selected highway contracts, and
3. As a part of the normal quality control tool on a nuclear power station site and a major airfield paving contract.

DESCRIPTION OF THE MACHINE

RAM, shown in Figure 1, is a floor-mounted automatic unit approximately 1 m² (3 ft²) in plan and 1.5 m (5 ft) high and about 160 kg (360 lb) in weight. About an 8-kg (17-lb) sample of fresh concrete is fed into a hollow cylindrical elutriation column. Water pumped from a reservoir in the machine up through the elutriation column liquefies the sample, and the cement along with some sand particles are lifted off as a slurry. At the top of the column is a sampling head where a tenth of the slurry is collected by weirs and directed into a 150-μm (no. 100) sieve, while the rest of the slurry is being carried to a waste container.

On the sieve the slurry sample is vibrated and washed by a water spray into a conical conditioning vessel where it is stirred and dosed with flocculating agents.

The base of the conditioning vessel is a detachable collecting pot or constant volume vessel (CVV) in which the solids are precipitated. The water in the conditioning vessel is syphoned off to a constant level within the CVV. The weight of the CVV containing solids and water is proportional to the weight of materials of cement fineness (apparent cement content) in the original mix. From a calibration curve (Figure 2) prepared for the machine, this apparent cement content can be obtained, and now a correction factor (Figure 3) for silt (finer than 150-μm sieve) present in the aggregate can be applied to get the true cement content of the mix.

It has been reported (1) that in a sand stockpile the ratio of weights of material passing the 150-μm sieve to materials held on this sieve but passing the 300-μm (no. 50) sieve is fairly constant. This relationship can be established from the proportional weight of the CVV with sand retained on the 150-μm sieve screened through a 600-μm (no. 30) sieve for a nominal mix.