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An investigation of the unit weight of concrete*

by Sándor Popovics, Dipl. Ing., Ph.D.

Contribution by Moritz Herbstein, B.Sc., D.I.C., A.M.I.C.E., A.M.I.Struct.E., A.M.A.S.C.E.
Gammon India Ltd, Bombay, India

Dr Popovics's experimental results are useful and interesting. His theoretical work is, however, unnecessarily complicated.

Given the aggregate/cement ratio, n, the water/cement ratio, w, and the mean specific gravity of the aggregates, G (determined by equation 11), the cement factor, c, in lb of cement per ft^3 of fresh concrete is given by

$$c = \left(\frac{1}{\frac{1}{3{\cdot}14\times 62{\cdot}4}+\frac{1}{62{\cdot}4}\left(w+\frac{n}{G}\right)}\right)\left(\frac{1}{1+v}\right) \quad \ldots\ldots\ldots(I)$$

in which the specific gravity of cement is taken as 3·14 and v is the air content of the concrete. For fully compacted concrete, i.e. zero air content,

$$c = \frac{1}{0{\cdot}00510+0{\cdot}01603\left(w+\frac{n}{G}\right)} \quad \ldots\ldots(II)$$

The cement factor, C, [in (94 lb) bags per yd^3 of fresh concrete] is given by

$$C = \frac{27}{94}c \quad \ldots\ldots\ldots\ldots\ldots(III)$$

The unit weight of fresh concrete may be expressed by equation 14

$$U_{\text{fresh}} = c(1+n+w) \quad \ldots\ldots\ldots\ldots(IV)$$

In Table I, values of C and U_{fresh}, calculated from the above equations (using the values of n and w given in Table 2, and putting $v = 0$) are compared with the author's results. The maximum discrepancy is less than 2%. The mixes selected for analysis all have $G = 2{\cdot}70$, except mix 35 for which $G = 3{\cdot}81$.

In Figure I, equations II and IV are shown in graphical form for $G = 2{\cdot}70$. Similar Tables may be prepared for other values of G. The bags referred to in Figure I weigh 112 lb.

Since Dr Popovics contends that the strength and workability of the concrete is not much affected by the substitution of other materials for the granite aggregate, it would appear that normal mix design methods[1,2] for strength and workability, used in conjunction with charts such as Figure I (plotted for various values of G) would provide a sound basis for the design of mixes to meet specifications of strength, workability and unit weight. It would be necessary to apply correction factors for estimated air content and weight loss due to drying out of the concrete.

Contrary to Dr Popovics's contention, the aggregate grading and the workability of a mix have, *in themselves*, no effect on the unit weight of concrete. (In Figure 4 and in Figure 5, both the aggregate/cement ratio and the water/cement ratio are variables for the values plotted.) They are important only in so far as they affect the air content of the mix. The cause of the tendencies demonstrated in Figures 4 and 5 is clearly shown by plotting the appropriate runs on Figure I.

Dr Popovics's conclusion that " . . . the increase of cement content . . . cause(s) reductions in the unit weight of normal and heavy-weight concretes " must be qualified.

Examination of Figure I shows that increased cement content will have the following effects:

at constant aggregate/cement ratio, the unit weight will increase;

at constant water/cement ratio, the unit weight will decrease.

Clarification from the author on the following points would enhance the value of the paper.

Are the results given in Tables 3 and 4 for single

*Pages 211 to 220 of *Magazine* No. 49.

TABLE I

1	2	3	4	5	6	7
Test	Cement factor, C (bags/yd^3)		(3) (2)	Unit weight of fresh concrete (lb/ft^3)		(6) (5)
	predicted from equations II and III	from Table 2		predicted U_{fresh} from equation IV	measured U_s (from Tables 3 and 4)	
1	6·25	6·25	1·000	150·1	150·0	0·999
2	6·12	6·13	1·002	148·3	148·3	1·000
11	4·86	4·85	0·998	149·4	149·2	0·999
12	4·76	4·78	1·004	147·5	148·2	1·005
15	7·90	7·84	0·992	151·3	149·9	0·991
16	7·73	7·72	0·999	149·4	149·1	0·998
19	6·29	6·17	0·981	147·4	144·6	0·981
20	6·16	6·07	0·985	145·6	143·7	0·987
23	6·18	6·20	1·003	150·8	151·2	1·003
24	6·08	6·12	1·007	149·4	150·4	1·007
35	6·26	6·29	1·005	197·5	198·5	1·005

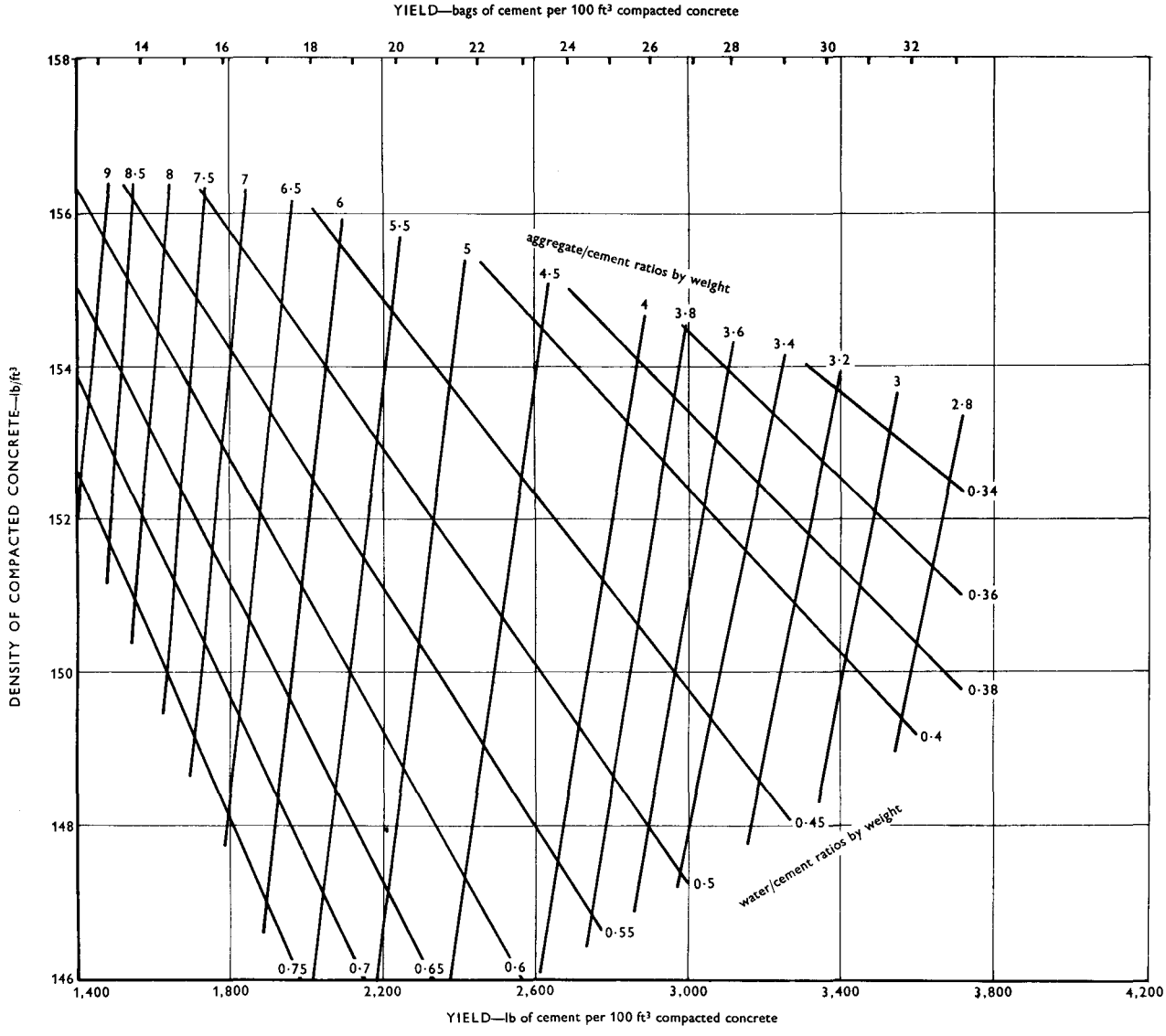

Figure I: Curves showing the relationship of cement yield and concrete density to water/cement and aggregate/cement ratios for a mean specific gravity of aggregate of 2·70.

tests or are they the means of several tests?

How were the volumes of the dry concrete cylinders determined?

Were the unit weights of any of the cylinders determined after the 6 days' moist-curing period? Is there any reason to expect a difference between the unit weight of fresh concrete and that of hardened concrete cured under water or at 80–100% R.H.?

In conclusion, it is suggested that the accurate determination of the unit weight of fresh concrete or of hardened cubes or cylinders at an age of 24 hours may prove a useful method of concrete quality control. It may, perhaps, be possible to correlate, for any given mix, the unit weight of fresh concrete (or of cubes or cylinders immediately after demoulding) with the 28-day strength. Research along these lines is suggested.

Reply by the author

The major part of Mr Herbstein's objections is due to a misunderstanding. As with many relations in concrete technology, the formulae for unit weight can be expressed either in terms of the amount of water and the water/cement ratio, respectively, or in terms of consistence. Both approaches are correct in principles; however, they result in formulae of different purposes. Thus, they cannot be used as substitutions for each other. Consequently, Mr Herbstein's proposal that formulae based on the water/cement ratio be used instead of formulae based on the concept of consistence is not acceptable. I admit that the formula with water/cement ratio can be useful in certain cases; for instance, when the aggregate/cement ratio and the water/cement ratio which are needed for a specified consistence are given, but these are rather exceptional cases. In most practical cases, the consistence is specified but the needed water content or water/cement ratio is not known. In the latter cases, the formula based on the water/cement ratio is not directly applicable, of course, but the formulae presented in the paper are. As the derivation of equations 2–9 shows, an extra step was required over and beyond the formula with water/cement ratio to fulfil this goal. Incidentally, the formulae with water/cement ratio were omitted intentionally from my paper mainly because the heart of the matter, i.e. equation I in the discussion by Mr Herbstein, had been published earlier.[3]

Similar misunderstanding appears in the statement by Mr Herbstein that I attribute effects to the aggregate grading and workability on the unit weight of concrete in themselves. There is no such statement in the paper. What is stated is that the use of over-sanded gradings causes a considerable reduction in the unit weight of fresh and of hardened concrete *if* the consistence and the air content are maintained constant; and this statement does not need any correction. The other objections concerning the effects of consistence and cement content can also be rejected in the same way.

Although I do not feel that the formulae presented in the paper are unnecessarily complicated, there is a possibility for simplification. The basis of this simplification is that, in the practical range, both the change in consistence due to the change in water content and the change in cement content only slightly affect the unit weight. Even a change in grading has little effect on the unit weight of concretes having constant consistence, provided that the aggregate is graded within the limits of generally accepted specifications. Thus, these variables in my formulae can be substituted by appropriate constants, resulting in very simple formulae for the prediction of U_s (fresh unit weight) and U_f (dry unit weight) for the usual range of structural concretes, as follows :

$$U_s = G(44{\cdot}5 - 0{\cdot}6v) + 33 \quad \text{.....(V)}$$

and

$$U_f = G(44{\cdot}5 - 0{\cdot}6v) + 25 \quad \text{.....(VI)}$$

where the symbols are identical with those in the paper. The approximation of these formulae is naturally not as good as that of the more sophisticated formulae.

As to Mr Herbstein's other questions, in most cases the U_s values represent the results of single tests; the other values in Tables 3 and 4 represent the averages of two determinations; the shrinkage of concrete was omitted in the calculation of hardened unit weights, which is more or less justified by the approximate nature of the formulae; and, measurements other than those presented in the paper were not performed.

Finally, if Mr Herbstein, while writing the last paragraph of the discussion, had in mind the compressive strength of a given concrete as a function of void content, I would agree with him that further research is desirable in this direction. Although published investigations[4-7] provide certain basis, as is shown in Figure II, nevertheless our present knowledge is

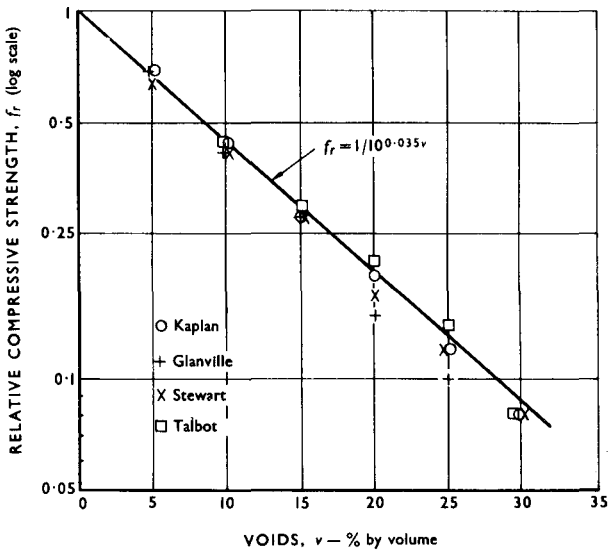

Figure II: Relative compressive strength as a function of unintentional void content of concrete.

rather incomplete on this subject.

I am grateful to Mr Herbstein for giving me the opportunity to express my ideas more clearly.

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