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The workability of concrete*

by L. J. Murdock, M.Sc., Ph.D., M.I.C.E.

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Dr Murdock's interesting paper describes what is undoubtedly a further important step in the development of concrete mix design.

The problem in mix design is that of knowing what aggregate grading and aggregate/cement ratio are required with a given water/cement ratio to produce the required workability. It is clear that the water in concrete which will affect workability is the free water, that is the water which is not used up in filling the pores in the concrete or in mixing with the cement powder. Singh in his paper⁽¹⁾ took cognizance of the water/cement ratio necessary to give a cement paste of standard consistence in the manner now adopted by Dr Murdock but, even though these facts were known, there was still a missing link, namely, the influence of aggregate grading and aggregate shape. Dr Murdock's paper supplies this link and deals with two important concepts, namely particle size and particle shape. Although I agree with Dr Murdock that the use of specific surface places too much emphasis on the smaller particle sizes, it is still possible to determine a relation between workability and specific surface as was done by Singh in his paper.

The surface index proposed by Dr Murdock gives due weight to the sand sizes which, in normal concreting practice, appear to be important. It is a little difficult to attach physical significance to the constant added to the summation of surface indices in Table 1 of Dr Murdock's paper. The historical derivation of this constant explains its presence, but there seems little reason why the actual value of the revised surface index should not be used without this constant.

With regard to the particle shape, it is clear that the

loose bulk density of a single-size closely graded aggregate must depend on three properties: a surface effect due to roughness and angularity, the specific gravity of the aggregate, and the manner in which the aggregate is compacted. If the aggregate is compacted into a mould in a uniform manner, a factor can be derived which will be a measure of the surface effect, that is the roughness and angularity. This, of course, is Shergold's⁽²⁾ test. If, however, the test is made in a different manner, a different measure of angularity will be obtained. This fact appears, at one time, not to have been fully appreciated by Dr Murdock who has suggested that the angularity index can be determined by using the compacting factor apparatus.⁽³⁾

I have had a number of tests carried out in which angularity factors were measured by these two different methods, and the results are given in Table I.

From this Table, it appears that the angularity factors measured by the two methods are not interchangeable. Furthermore, there seems to be no significant relation between the two, although there is a relation between the percentage voids determined by these two methods, as is shown in Figure 1. The relation previously obtained by Kaplan⁽⁴⁾ is also shown in this Figure. Whilst these do not agree, it is clearly possible to use the compacting factor apparatus as long as a correction is applied to the voids ratio before the angularity index is calculated.

From a limited number of tests, it appears that the angularity may be determined by compacting the dry aggregate in the compacting factor mould by vibrating it on a vibrating table. This result might be expected since the method proposed by Shergold ensures that the maximum bulk density is obtained. The reproducibility of the angularity index appears to be better when the compacting factor method is used than when the Shergold method is used or when the results are obtained by vibrating. Incidentally the determination of the angularity factor on each of the single sizes of

*Pages 135-144 of *Magazine* No. 36.

TABLE I

Material	Size	Angularity index f_a' determined by	
		B.S. 812 method	Compacting factor apparatus
Slightly rounded flint gravel	$\frac{3}{4}$ – $\frac{3}{8}$ in.	1.44	2.24
	$\frac{3}{8}$ – $\frac{3}{16}$ in.	1.87	—
Irregular flint gravel A	$\frac{3}{4}$ – $\frac{3}{8}$ in.	1.91	2.77
Irregular flint gravel B	* $\frac{3}{4}$ – $\frac{3}{8}$ in.	2.08	3.04
	$\frac{3}{8}$ – $\frac{3}{16}$ in.	2.47	3.14
Angular granite	$\frac{3}{4}$ – $\frac{3}{8}$ in.	2.62	3.80
Crystalline limestone	$\frac{3}{4}$ – $\frac{3}{8}$ in.	2.53	3.95
Quartz sand	$\frac{3}{16}$ in.–No. 7	2.47	3.44
	No. 7–No. 14	2.47	3.38
	No. 14–No. 25	2.25	3.15
	No. 25–No. 52	1.62	2.56
	No. 52–No. 100*	1.84	—

*Proctor compaction mould used.

Figure I: Relation between angularity (as percentage voids) measured by the British Standard method and measured by the compacting factor apparatus.

sand is somewhat tedious and in normal practice I doubt whether it would be carried out. The results that we have obtained, however, appear to give a somewhat higher value for Thames Valley sand (ex Ham River) than that obtained by Dr Murdock.

One drawback with the use of the surface and angularity index is that theoretically one needs to know the values of f_s and f_a before the mix can be designed, whereas in fact they are only known afterwards. This is overcome by means of the usual engineering guess-estimate but it does give weight to a criticism of Dr Murdock's method, that it is like other methods of mix design such as the Road Note 4 method: it is very good as long as one is skilled at mix design in the first place !

Contribution by B. P. Hughes, Ph.D., B.Sc.
(John Laing & Son Ltd)

I should like to refer to the very interesting paper by Dr Murdock on the workability of concrete. The relation for the calculation of compacting factors should prove most useful because of its ready and simple application to mix design. There are one or two items, however, which appear to require some clarification.

Dr Murdock states on page 136 that "... all attempts to include the surface area coefficient of cement in assessments of workability have failed. For this reason, the surface area coefficient of the cement has previously been neglected, although this appeared illogical". I entirely agree that the cement should be considered together with the aggregate. This has been done in Figure II, which shows a relation I obtained a few years ago at the University of Birmingham⁽⁵⁾.

The degree of scatter appears directly comparable with that for Dr Murdock's relation. In my notation, a , b , c and w are the specific volumes (gross apparent volume per unit volume of concrete) of the coarse aggregate, fine aggregate, cement and water respectively⁽⁶⁾, whilst $\alpha_a G_a$ and $\alpha_b G_b$ are forms of surface area coefficient of the coarse and fine aggregate respectively. The value of 3,000 indicates a surface area expected of particles between B.S. sieve Nos. 200 and

Figure II: Alternative relation for compacting factor suggested by Dr Hughes.

Figure III: Curves for the same basic consistence.

400, i.e. a little coarse but not unreasonable for this application. e is the specific volume of the aggregate passing B.S. sieve No. 120. Different types of coarse aggregate give slightly different curves, so that a further factor for the particle shape of the coarse aggregate, *different from the angularity factor, α_a , must be introduced to obtain a single curve. This agrees with Dr Murdock's item (2) on page 135.

The point I wish to emphasize is the complex nature of the workability relation. Introduce enough arbitrary parameters and it is usually possible to obtain a reasonably accurate mean relation for almost anything. This in no way detracts from the ingenious way in which Dr Murdock has made his assumptions in order to obtain a relation which is quickly and easily applied, but let us not forget that many other basic assumptions can be made to obtain just as accurate a relation.

I strongly endorse the view, given on page 138, "that workability should be assessed on the basis of the volume of the constituents of the concrete". I have never understood why greater use of absolute volumes has not been made in Britain. This concept is also extremely advantageous for other properties of concrete besides workability.

The simple Vicat test which "simplifies the problem of determining the water content available for lubrication of the mix" (page 139) is usefully applied but is a little misleading to the reader. The implication is that the water requirement of the cement is constant at around 0.25 for all aggregate contents. This is not true, of course.

Talbot and Richart⁽⁷⁾ and Weymouth⁽⁸⁾ showed that there are three factors to consider when adding aggregate to cement paste, for a given "basic" consistence.

- (1) The water required to give a critical consistence for the cement alone (equal to a water/cement ratio of around 0.25 as above).
- (2) The addition of saturated, surface-dry sand to the cement paste stiffens the mixture as the result of a "boundary effect". This is the normal effect of reducing the bulk density of a granular material by increasing the boundary surfaces. If the bulk density of the cement is reduced, the voids are increased so that more water must be added to restore the original consistence and eliminate air voids.
- (3) Further addition of sand eventually reduces the spacing between the sand grains to little more than the particle size of the cement. Distribution of cement between the sand becomes restricted and a further effect, that of "particle interference", occurs when more sand is added. Further water must therefore be added to make good these additional voids in the cement.

The foregoing effects are illustrated in Figure IIIa which has been taken from Weymouth's paper⁽⁸⁾. Curve w/c represents the reduction in voids due to the reduction in the volume of cement paste, per unit volume of mortar, as the sand is added. The difference between this curve and the appropriate curve B is the "boundary surface" effect while the difference between the actual curve and curve B is the "particle interference" effect.

Figure IIIa can be replotted in the form shown as Figure IIIb. It is now evident that the total "lubrication" requirement of the cement varies approximately linearly with b/c over the practical range for sand 3, a normal well graded sand. Sand 23 is much finer so that well designed mixes require a smaller proportion for a given total aggregate/cement ratio (i.e. A_v). Sand

36 is a coarse sand normally considered too harsh for the leaner mixes. It is for these reasons that the factor of 0.25 is satisfactory in Dr Murdock's relation on page 140.

Table 5 (page 141) omits those results where segregation was recorded. Would Dr Murdock please indicate in what sense the term is used here? Is it segregation of the constituents before compaction, as judged by visual examination, or is it segregation during compaction, due to a deficiency of fines, as referred to later on page 141?

Concerning the comparison with Newman and Teychenné's results; the two mixes, B and J, which give poor agreement have the lowest coarse aggregate ($\frac{3}{4}$ – $\frac{3}{8}$ in.) contents. I would be very interested to know if the tests at Southall included grossly over-sanded mixes. Only some of the 300 trial mixes referred to on page 141 appear to be given in *Research and Application*. If reasonably well designed mixes are assumed in Figure 4, then sand contents would be extremely low at A_v values of around 2. This would further reinforce the effect noted at the top of page 139.

Contribution by D. C. Teychenné, B.Sc.(Eng.) (Building Research Station)

It has long been accepted that the physical characteristics of the aggregate such as its maximum size, grading, particle shape, surface texture and absorption affect the workability of concrete. Dr Murdock has made a very interesting attempt to develop a method of mix design which takes into account most of these factors without having to carry out difficult and lengthy tests on the aggregates.

Dr Murdock's equation 5 for calculating the compacting factor of a concrete mix undoubtedly gives good correlation with the experimental data obtained at Southall, but this correlation is not obtained when this equation is applied to the results of tests made at the Building Research Station as shown in Table 6 of the paper and, in respect of more recent data, in Figures IV and V below. In the present note, answers are given to the questions raised by Dr Murdock concerning the data obtained at the Building Research Station and given in Table 6.

The water/cement ratio stated is the *total* water/cement ratio based on dry aggregates and the compacting factor test was carried out immediately after mixing. There is likely to be little difference in the angularity of the aggregates since it is believed that the same type of river sand and gravel was used at both laboratories. The use of a different cement should not have a great effect and any such effect should appear as a constant difference for the various mixes considered.

As a result of these different conditions of test, a consistent difference between the calculated values of

the compacting factor and those obtained experimentally at the Building Research Station would be expected, but it is difficult to reconcile the range of calculated compacting factors in the series of mixes A to I (0.77 to 0.95+) with the fairly uniform values obtained experimentally. This leads on to the last point raised by Dr Murdock which infers that some mixes may have been of different workability although the compacting factors were very similar. It is agreed that the compacting factor is not an absolute measure of that rather intangible term "workability", and that mixes having the same compacting factor may have differences in properties, such as the ease of trowelling, which are included in the term "workability". However, the workability of the mixes A to I did not vary to the extent suggested by a variation in compacting factor of from 0.77 to 0.95+ as calculated from Dr Murdock's formula. Furthermore the data abstracted in Table 6 were originally given in a paper by Mr A. J. Newman and the present writer⁽⁹⁾, and included the results of Vebe tests, which show little correlation with Dr Murdock's calculated compacting factors; in fact, for the mixes which gave calculated compacting factors of 0.77 and 0.95+, the results of the Vebe tests were almost identical at 15.7 and 15.0 respectively.

Since the publication of the paper referred to in the previous paragraph, a further programme on the use of surface area in mix design has been carried out at the Building Research Station, the results of which have not yet been published. In this programme, dry aggregates were used but the compacting factor was not measured until 10 min after mixing. This measured compacting factor is plotted in Figures IV and V against that calculated from Dr Murdock's formula. The values of the surface index (f_s) were calculated for the 10 different gradings used, the angularity index (f_a) was assumed to be 1.9 and the aggregate/cement ratio by volume (A_v) was calculated on the basis of an average specific gravity of 2.54 for the irregular river sand and gravel used. The calculations for Figure IV were based on the total water/cement ratios, and those for Figure V on the water/cement ratio modified to allow for the full absorption of the aggregate. Neither of these sets of data agrees well with the measured values and perhaps the adoption in calculation of an intermediate value for water/cement ratio which only allows for some of the absorption would give closer agreement between the measured and calculated values. When the total water/cement ratios are used, a considerable number of the calculated compacting factors are greater than 1. In both Figures IV and V, there is a scatter of about 0.175 in the calculated values for a given practical compacting factor. The difference in the values of the calculated compacting factors shown in Figures IV and V shows the importance of accurate definition and calculation of the water/cement ratio.

Figure IV: Comparison between compacting factors measured at the Building Research Station and values calculated according to Dr Murdock's formula, on the basis of total water/cement ratio.

Figure V: Comparison between compacting factors measured at the Building Research Station and values calculated according to Dr Murdock's formula, on the basis of water/cement ratio modified to allow for the full absorption of the aggregate.

It is considered that the large difference between the experimental results obtained at the Building Research Station and the calculated compacting factors, as shown in Table 6 of the paper and in Figures IV and V, are due to the fact that Dr Murdock's values of the "surface index" do not reflect the relative importance of the different size fractions in the grading of the aggregate. As the result of the computer analysis, he has removed the emphasis from the importance of the finer sizes in mix design, and it is now difficult to associate the true surface area of a graded aggregate with his surface index (f_s). From the evidence in Table 6 and in Figures IV and V, it is suggested that the

values of the surface index (f_s) which have been obtained from the criterion of "best fit" for a given set of data should not be more generally used.

In the outline of mix design procedure, Dr Murdock has not explained how the suggested values of f_s for the different maximum sizes of aggregate were obtained. The procedure also implies that f_s should be constant irrespective of the aggregate/cement ratio, although it is generally recognized that leaner mixes require a higher sand content, which would increase the over-all specific surface, and it would appear that the surface index f_s should also be increased in a similar way.

Contribution by K. Newman, B.Sc.(Eng.),
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of Science and Technology)

Dr Murdock is to be congratulated on this real attempt to produce a simple relation between mix characteristics and the workability of concrete. The replacement of current British mix design methods by a single standard procedure covering all types of cement and sizes and types of aggregate is long overdue. Although, in my view, Dr Murdock's approach is correct in principle, several limitations are made apparent by the conclusions drawn.

First, it must be pointed out that, by using Dr Murdock's procedure, one is *designing concrete mixes for the compacting factor apparatus*. Consequently the resultant concrete may not necessarily be suitable for the job in hand. As long as workability is defined only in terms of the compacting factor test, then such anomalies as an apparent improvement in workability with an increase in the fineness of sand will arise.

If the properties of fresh concrete are to be described completely, the definition of workability and methods of testing must be a measure of not only how much work is required to compact the concrete and remove air voids (compactability), but also the ease with which the concrete can flow into formwork between steel bars and be remoulded (mobility), and its ability to remain a stable homogeneous mass during handling and compaction without segregation of the constituents (stability). A single test method to assess this composite property has yet to be devised. However, compactability, which is determined by the amount of internal work required to compact concrete fully, can be measured indirectly by the compacting factor test, the relative mobility can be assessed by means of a remoulding test⁽¹⁰⁾, and stability by a segregation or cohesion test⁽¹¹⁾.

Such an approach may seem too complex to many who regard workability as being defined only in terms of compactability⁽¹²⁾. However, compactability and compacting factor measurements alone will not completely differentiate between mixes, as an estimation of mobility and stability will depend on a visual appreciation of concrete.

The effect on fresh concrete of varying the mix proportions can more easily be understood if concrete is regarded as a mixture of large particles surrounded by a lubricating film. In concrete the lubricating film is mortar, and in mortar the lubricating film is cement paste. The capacity of larger particles for movement through the matrix without interference will depend on the thickness and consistence of the lubricating film. It has been shown⁽¹³⁾ that, in general terms, workability is improved by an increase in the thickness of the lubricating film (which is a function of the paste content by volume p , the surface area s , and the voids ratio v , of the combined aggregates) and the consistence

of the film (which is a function of water/cement ratio w/c); and adversely affected by the angular shape and rough surface texture a , and the interference i_p , between large particles of the aggregates or,

$$\text{workability} \propto \frac{p w/c}{svi_p a}$$

It is interesting to compare this general relation with the function for compacting factor,

$$\frac{w/c - 0.25}{f_s f_a (A_v - 2)}$$

Dr Murdock's factor for paste consistence is $w/c - 0.25$, which takes into account the water/cement ratio required to "wet" the cement. The increase in workability with paste content is expressed as the inverse of $A_v - 2$. Both relations indicate that workability varies inversely with angular shape and rough surface texture of the aggregate. There remains the surface index f_s to be compared with specific surface s , voids ratio v and particle interference i_p .

It must be emphasized that the surface indices f_s are based on results obtained using the compacting factor test to assess workability. The compacting factor test is a measure of density, and its use places undue emphasis on those grading characteristics which help to improve the density of concrete when it is acted on by the small forces applied by the test. When the maximum size of aggregate in a mix is increased, say from $\frac{3}{4}$ to $1\frac{1}{2}$ in., there is a slight reduction in the surface area of the aggregate. Of more significance, however, is the increase in bulk density and decrease in voids ratio of graded coarse aggregates obtained as the maximum particle size increases. Thus, for the same over-all specific surface, a greater weight is obtained in the compacting factor cylinder with $1\frac{1}{2}$ in. aggregate. However, the increase in compacting factor does not necessarily mean an increase in the compactability of the mix.

Moreover, the surface index suggests that an improvement in workability can be obtained by using finer sand. Concrete mixes which are dry, or have a low cement or sand content, tend to be harsh and unworkable. With these mixes, an increase in the percentage of fine material can improve mobility by helping to fill the voids and decrease particle interference during handling. The resulting increase in density of the uncompacted concrete produces an increase in the compacting factor value. However, when dry harsh mixes are vibrated, the greater surface area of fine particles of sand becomes effective, increasing the amount of effort required to compact the mix. With rich, workable mixes, the compacting factor is not so sensitive to changes in the sand grading and large alterations in f_s values would have little effect.

The surface index, therefore, would appear to be a combination of specific surface, voids ratio and particle interference and might be termed the "effective

Figure VI: Relation between consistence of neat cement paste and water/cement ratio for different cements.

specific surface" for the compacting factor test. The surface index values will not apply to dry mixes designed for vibration, or mixes where there is no coarse aggregate particle interference, such as mortars. This is further supported by Cusens's evidence⁽¹⁴⁾ that, below a value of 0.80, the compacting factor test does not give a true indication of the amount of work required to compact the concrete fully.

Nevertheless, despite the limitations of the f_s values, Dr Murdock's approach is fundamentally correct. The compacting factor test will probably be used to define workability, by itself, for some time yet and his procedure is a great improvement on current methods of design. Therefore, one or two comments on the use of the equation for compacting factor are appropriate.

High water/cement ratios, in conjunction with high cement contents, in equation 5 can produce compacting factor values greater than 1. This is due not so much to an error in the equation as to certain limitations in the factor $w/c - 0.25$. Figure VI (which has been adapted from Figure 4 of reference 15) suggests that workability is related not to the water content by volume but to the consistence of the cement paste. Above water/cement ratios of about 0.75–0.80, all cement pastes have a consistence equivalent to that of water. Therefore, the factor $w/c - 0.25$ can never have a value greater than about 0.50–0.55. If this upper limit is applied, equation 5 will not produce compacting factors greater than 1. However, the straight central part of the curves in Figure VI does indicate that workability is directly related to water content over a certain range of water/cement ratios.

The water/cement ratio values at zero consistence indicate the amount of water required to "wet" the cement particles. This value, which is related to the

immobile water factor w_i defined by Powers⁽¹⁶⁾, varies from about 0.30 for rapid-hardening Portland cement to 0.25 for ordinary Portland cement down to less than 0.20 for high alumina cement. The use of such values of x in the factor $w/c - x$ provides a satisfactory explanation of the variations in workability reported with different cements^(15,17). It is surprising that Dr Murdock did not emphasize this point.

As the workability of concrete is affected by the consistence of cement paste and not the water content by volume, it is pointless to try to include the specific surface of cement with the characteristics of the aggregate. The specific surface of cement is only of importance in that it affects the consistence of the cement paste.

The stumbling block in any mix design method is the choice of the optimum proportions of sand and coarse aggregate to satisfy the requirements of workability. It is a pity that Dr Murdock has rather avoided the issue by simply suggesting certain, apparently arbitrary, values of surface index f_s for different maximum size aggregates. Do these values apply to lean, rich or average cement content mixes? It is well known that the optimum sand content decreases as the cement content increases.

Furthermore, how does Dr Murdock define segregation? In the latest edition of his book⁽¹⁸⁾, lower limits are given for f_s to prevent segregation occurring. How were these values determined? For large values of f_s and lean mixes, there could be insufficient paste to fill the voids in the combined aggregates, and complete compaction could prove impossible. It would be useful if Dr Murdock could suggest some upper limits to values of f_s .

I realize that there cannot be a definite answer to these questions because assessment of the properties of concrete by the compacting factor test alone will not provide them. Limits to f_s values depend as much on the requirements of mobility and stability as on compactability. Other tests are required to express the properties of concrete completely and give an indication of the nature of the deficiency of an unsatisfactory mix.

Finally, concerning the comparison with Newman and Teychenné's results, it would be interesting to know how the weight of the fully compacted concrete was found when calculating the author's test values of compacting factor. It has been shown⁽¹⁹⁾ that compacting factor values vary considerably depending on assumptions made when calculating the theoretical wet density of concrete. Do I understand from the paper, that, whilst Newman and Teychenné used a total water/cement ratio of 0.55 (corresponding to an effective water/cement ratio of about 0.47), Dr Murdock used an effective water/cement ratio of 0.55? If so, Dr Murdock's test method should produce higher compacting factor values, which is the case, at least with mixes D, I and K. In addition, recent work at

Imperial College has shown that, for complete saturation to occur, air-dry aggregates must be completely immersed in water. Addition of the absorbed water only, before mixing, does not guarantee saturation. Admittedly the effect on workability is small compared with the effect on strength.

These criticisms are not intended in any way to detract from the value of the paper. An approach similar to Dr Murdock's is required if a single design procedure covering all concrete mixes is to be developed. By extending the compacting factor relation to include the properties of mobility and stability of a mix, the workability of concrete will at last be able to be related completely to the mix characteristics.

Contribution by W. E. Murphy, B.Sc.(Eng.)
(Cement and Concrete Association)

Dr Murdock has developed a very interesting and useful formula relating the compacting factor of fresh concrete to the properties of the aggregates, the mix proportions and the water/cement ratio. This formula has been examined in connexion with a few mixes made at the laboratories of the C & C A at Wexham Springs in the course of other investigations. The first series of mixes contained $\frac{3}{4}$ in. maximum size irregular gravel, natural sand and a uniform consignment of ordinary Portland cement. The series consisted of four sets of four mixes, the different sets having aggregate/cement ratios of 3, $4\frac{1}{2}$, 6 and $7\frac{1}{2}$ by weight respectively. The water/cement ratios of the four mixes of each richness were varied to give a range of workability. The gradings of the sand and the coarse aggregate were maintained constant, but the sand fraction of the total aggregate was varied as considered necessary for each mix.

The aggregates were soaked in the mixing water for 24 h before the cement was added; the partially compacted weight for the compacting factor test was determined at times of 3 and 60 min after mixing. Assuming that the compacting factor decreases approximately linearly in respect to the logarithm of the time after mixing, the average of the two test results was regarded as the workability at a time of $13\frac{1}{2}$ min after mixing.

Figure VII shows the graph obtained when the 16 values of compacting factor obtained are plotted against $10(w/c - 0.25)/f_s f_a (A_v - 2)$. From formula 4 of Dr Murdock's paper, the points would be expected to lie close to a single straight line. In fact, it is evident that they are scattered to a considerable extent, there being a distinct tendency for the compacting factor of a lean mix to be higher, for a given value of $10(w/c - 0.25)/f_s f_a (A_v - 2)$, than that of a rich mix.

Dr Murdock has suggested that the formula could be improved by varying the constant deducted from the water/cement ratio according to the characteristics of the cement. He suggests that the figure to be

Figure VII: Relation between compacting factor and $10(w/c - 0.25)/f_s f_a (A_v - 2)$ for the first series of C & C A tests.

adopted should be the highest water/cement ratio that will prevent complete penetration of the Vicat plunger into a neat cement-water paste. This seems equivalent to stating that the figure to be used is the standard consistence of the cement as determined in accordance with B.S. 12:1958. The standard consistence of the cement used in this series of tests was 0.28 and Figure VIII shows that the points obtained on plotting the values of compacting factor obtained to a base of $10(w/c - 0.28)/f_s f_a (A_v - 2)$ lie more closely about a single straight line. This offers some evidence that Dr Murdock's formula can be generalized by stating that the compacting factor is a function of

$$\frac{10(w/c - s_c)}{f_s f_a (A_v - 2)} \dots \dots \dots (4a)$$

where s_c is the standard consistence of the cement.

The mixes described above made possible an examination of the results obtained on applying formula 4 to mixes of various richnesses. A further series of test results has been examined to assess the result of applying the formula to mixes containing aggregates of differing maximum size. The mixes were made with different water/cement ratios to cover a range of workability, there being a total of 46 mixes. All the mixes were made with an aggregate/cement ratio of 6.0 by weight.

The aggregate for each batch was covered with the mixing water for 15 min; the partially compacted weight for the compacting factor test was measured 3, 15 and 30 min after mixing and the average of the three values was regarded as the workability 11 min after mixing.

The standard consistence of the cement used in this investigation was again 0.28 and so, if formula 4a is assumed to apply, the values of compacting factor ob-

Figure VIII: Relation between compacting factor and $10(w/c - 0.28)/f_s f_a (A_v - 2)$ for the first series of C & C A tests.

tained would once more be expected to be related to $10(w/c - 0.28)/f_s f_a (A_v - 2)$. The graph obtained on plotting the compacting factor against this function is shown in Figure IX. It was found that the scatter obtained was not significantly different from that resulting from plotting the compacting factor to a base of $10(w/c - 0.25)/f_s f_a (A_v - 2)$. This is as expected, since the series did not contain any rich mixes.

Whether formula 4 or 4a is assumed to apply, a large proportion of results showed poor correlation where mixes made with aggregate of $\frac{3}{8}$ in. maximum size containing 30% sand were concerned; regardless of the formula used, 5 of the 6 measured values were below the general run of points. In these mixes, 70% of the aggregate consisted of single-sized $\frac{3}{8}$ to $\frac{1}{16}$ in. material and it would appear to be possible that the relation between compacting factor and specific surface often does not apply very accurately when there is an excess of any given size.

Further evidence of this is obtained on applying Dr Murdock's formula 5 to mix 145 of Table 10 of his reference 11. This mix contained, comparatively, a very high proportion (36%) of aggregate between the No. 14 and No. 25 sieve sizes. When Dr Murdock's formula 5 is applied to the data given, the calculated values of compacting factor are found to be 0.77, 0.84 and 0.90 corresponding to the three values of water/cement ratio, in contrast to the actual values of 0.72, 0.78 and 0.82. It is possible that this discrepancy may be due to limitations of the compacting factor test as a means of determining workability rather than to a fault in Dr Murdock's formula.

From formula 4a it would appear that the compacting factor cannot be related to the mix proportions unless the standard consistence of the cement is determined. In many cases, however, the cement

Figure IX: Relation between compacting factor and $10(w/c - 0.28)/f_s f_a (A_v - 2)$ for the second series of C & C A tests.

characteristics are not known; in such cases, it would appear logical to assume that the cement has a standard consistence of about 0.29, this probably being the best estimate of the average value for British ordinary and rapid-hardening Portland cements. This suggests that it should be assumed that the compacting factor is a function of

$$\frac{10(w/c - 0.29)}{f_s f_a (A_v - 2)} \dots \dots \dots (4b)$$

Ten of the series of mixes of different richness were repeated with a more rounded aggregate and another ordinary Portland cement, the standard consistence of which was not determined. It was found that this was a case where formula 4b applied more closely than the formula 4 of the paper.

The modification of formula 4 to account for the setting characteristics of the cement would be expected to affect the constants of 0.74 and 0.67 in Dr Murdock's formula 5. Owing to differences in testing technique, the compacting factor results obtained in the tests made at Wexham appeared to be about 0.04 higher than would be obtained by Dr Murdock when testing similar mixes. In spite of this, however, the constant 0.74 of formula 5 did not appear to be affected by the standard consistence of the cement or the testing technique. The additive constant of 0.67, however, did appear to depend on the standard consistence of the cement and analysis of the results indicated that, if Dr Murdock's testing technique is used, the compacting factor is given by the formula

$$c_f = 0.74 \left(\frac{10(w/c - s_c)}{f_s f_a (A_v - 2)} + (1.67s_c + 0.25) \right) \dots (5a)$$

Formula 5 is a particular case of formula 5a. If formula 4b is applicable to cement of average standard consistence, the best estimate of the compacting

TABLE II: Values of surface index.

Sieve sizes between which particles lie	Surface index for particles between sieve sizes indicated		Example of calculation for R.R.L. Grading No. 1, 1½ in. maximum size		
	Dr Murdock's values <i>f_s</i>	Alternative values <i>f_s'</i>	Percentage of particles within sieve range	<i>f_s</i>	<i>f_s'</i>
3 in.-1½ in.	0.8	—	—	—	—
1½ in.-¾ in.	1.3	1	50	65	50
¾ in.-⅜ in.	2.3	3	14	32	42
⅜ in.-⅙ in.	4.3	5	12	52	60
⅙ in.-No. 7	7.3	7	6	44	42
No. 7-No. 14	10.3	9	6	62	54
No. 14-No. 25	12.3	11	5	61	55
No. 25-No. 52	12.3	12	4	49	48
No. 52-No. 100	10.3	10	3	31	30
Passing No. 100	5.3	5	—	—	—
			Total	396 × 10 ⁻³ = 0.396	381 × 10 ⁻³ = 0.381

factor of a mix having a cement of unknown standard consistence would appear to be given by the formula

$$c_f = 0.74 \left(\frac{10(w/c - 0.29)}{f_s f_a (A_v - 2)} + 0.73 \right) \dots\dots\dots (5b)$$

In connexion with the use of the information given in the paper for the design of concrete mixes, Dr Murdock suggests that the angularity index of the aggregate may be assessed approximately from the examples he quotes or, more exactly, may be determined by tests. If values are taken from Table 2 or 3 of the paper, the subsequent error in compacting factor may be 0.08 or more since, for example, the angularity indices of crushed limestones tested at Wexham have ranged up to 2.65 compared with the author's value of 2.05 for Mendip limestone. If tests are made, it would appear to be unnecessary to test each half-size present in the material to be used and it would be of interest if Dr Murdock could give some guidance as to the number of sizes that should be tested to assess the over-all angularity index of a graded material.

Perhaps one of the most interesting parts of the paper is that dealing with the calculation of surface index, since the figures quoted can be used in any method of mix design which necessitates the determination of the proportions in which to combine available aggregates to give a grading equivalent to that assumed in the course of the design procedure. Dr Murdock has implied that some improvement in his method of design may be possible if the given values are modified in the light of further experimental evidence. In view of this, it would be interesting if he could give some guidance on how his figures were obtained. It is apparent, as indicated in Table II, that the values he quotes for the various single sizes are effectively 0.8, 1.3, 2.3 . . . 5.3 and that the arithmetic has been simplified by reducing each value by 3.3 and

adding a constant of 330 to the sum of the component indices. The scatter of the results plotted in Figure 1 of the paper, however, appears to be such that the surface indices could be represented by a series of simple integers. As an example of a possible alternative set of values, the surface indices of the gradings used in the series of tests mentioned above were calculated using the second set of values quoted in Table II. From the results of the tests on all the 62 mixes discussed in this contribution, it appeared that the measure of agreement between calculated and actual values of compacting factor was not significantly affected by using these alternative values of surface index.

Dr Murdock has suggested values for the desirable surface index of combined aggregate depending upon the maximum size and the expected variation in grading of the component materials. The optimum value would also be expected to depend on the workability of the concrete and the richness of the mix as well as the handling conditions. In view of this it would be interesting to have Dr Murdock's views on the following procedure. First the water/cement ratio is determined from considerations of strength and durability and, if the required compacting factor is less than 0.84, one of the following empirical formulae is used to determine the optimum value of surface index.

- For aggregate of 1½ in. maximum size:
 $f_s = 0.25c_f w/c + 0.40 \dots\dots\dots (6)$
- For aggregate of ¾ in. maximum size:
 $f_s = 0.25c_f w/c + 0.45 \dots\dots\dots (7)$
- For aggregate of ⅜ in. maximum size:
 $f_s = 0.25c_f w/c + 0.55 \dots\dots\dots (8)$

If the required compacting factor is greater than 0.84, the values of surface index obtained from the above formulae would probably only be suitable if the aggregate grading could be expected to be particularly uniform and conditions were such as not to

encourage segregation. Under less favourable conditions it would be advisable to increase the values of surface index by up to $(c_f/2 - 0.42)$, the amount of the increase depending on the conditions in any particular case.

Reply by the author

It is gratifying to find that several contributors to the discussion have indicated a considerable measure of agreement with the new approach which I put forward. In my reply I will deal as fully as possible with the many points they have raised.

I agree with Mr Akroyd that a relation can be established between workability and specific surface, but this breaks down when mixes are used in which the maximum size of aggregate is varied, or the proportion of fine aggregate passing a No. 100 sieve is varied, and is true for one particle shape only. The increase in specific surface with increase in angularity does not appear to be related to the decrease in compacting factor which occurs. In my opinion, the intermediate sizes provide more resistance to mobility in the concrete than the finer sizes; if the specific surface is regarded as the index of grading, this effect is not accounted for. The values obtained for the surface index seem to be in keeping with my view.

As Mr Akroyd says, it is difficult to attach physical significance to the constant added to the summation of indices in Table 1, except that its effect is to reduce the influence of aggregate grading in the relation I have established. Further research may suggest a refinement of the values I have obtained. From the analyses I have made with a number of combinations of values of surface indices, and from the comparatively small improvement obtained by taking the computer values, compared with those used in the original analysis, it does not seem that the actual values are very critical, provided they follow the general form of the curves given in Figure 1.

Mr Akroyd comments on the method of measuring particle shape or angularity. He is quite correct in stating that the method adopted was that suggested by Shergold and that a different value is obtained by the compacting factor apparatus. Unfortunately, there was an error in early copies of *Concrete Materials and Practice* regarding this point; later copies contain a correction slip. Since the compacting factor method is less variable, I think it may be more acceptable, provided a correction is made. I suggest this might be:

$$V = 0.7V_o + 5.5$$

where V is the percentage voids by Shergold's method

V_o is the percentage voids by the compacting factor method

This gives good agreement with the relations established by Akroyd and Kaplan.

Mr Murphy has indicated the range in values of

angularity indices which can be obtained with crushed limestones. Whilst it will be evident that much further information is now needed on the angularity of aggregates, I suggest for the moment that one or two tests on, say, the coarsest and finest sizes of coarse aggregate should be sufficient.

I also agree with Mr Akroyd that the angularity determination is tedious if done on all the single sizes of sand. I suggest that a fair approximation might be obtained by taking, say, two or perhaps three sizes only.

Sand supplied in the Thames Valley is apt to contain angular particles owing to the inclusion of crushed material returned from the crushers which deal with oversize material for which there is no demand. In the tests described in my paper, a great deal of trouble was taken to obtain sand which did not contain crushed particles. In practice, the presence of varying quantities of crushed particles can affect the workability quite substantially; in fact, inspection of the suggested formula and the comparative range in values for surface indices and angularity indices would appear to suggest that changes in angularity are likely to be of greater importance than changes in grading.

I do not understand Mr Akroyd's reference to the values of f_s and f_a only being known after the mix has been designed. It is usual to do a sieve analysis of aggregates to be used in concrete before designing the mix, and tests could be done for f_a at the same time. An alternative method of dealing with the question of angularity is to make up a trial mix and measure its compacting factor. With the other variables already known, a value for f_a can then be calculated and used to determine the influence of variations in mix proportions and grading from those used in the trial mix.

Dr Hughes has presented interesting data which, allowing for the difference in approach, do not appear to contradict the evidence produced in my paper. The main object of my paper was to establish the dominant factors influencing workability and to explain their interrelation in as simple and logical a manner as possible. By doing so, I hope that, while I have established a mathematical relation for use with the compacting factor, the basic principles put forward may, with suitable adjustment, be applied with other methods of assessing workability. I think this is where the approach I have made differs from that suggested by Dr Hughes, who, in his published paper⁽⁶⁾ includes the following sentence: "Unfortunately, the relations obtained for the workability of concrete were too complicated for general application to mix design".

Reference is made to Talbot and Richart⁽⁷⁾ and Weymouth's⁽⁸⁾ work on cement mortars. The curves in Figure IIIa suggest to me that the boundary effect chiefly influences mixes with sand/cement ratios richer than 2. With the addition of more sand, particle interference occurs. In my paper, however, I have not attempted to deal with very rich mixes and, in fact,

the richest mix for which I made tests was 1:3½ cement:total aggregate.

Dr Hughes and Mr Newman refer to the question of segregation, to which reference was made in Table 5. This was in all cases associated with a surface index of 0.50 or less, and resulted from a deficiency of fines. Reference is made to this point again towards the end of this reply.

The tests at Southall included a few mixes which might be regarded as grossly over-sanded, the maximum sand content used being 73%. There was a tendency to underestimate the compacting factor for these over-sanded mixes. All the trial mixes referred to on page 141 are given in *Research and Application*, since there are three different water/cement ratios for each mix number.

The fact that Mr Teychenné, in the tests made at Building Research Station, has not obtained good correlation with my approach is not surprising, in view of the method adopted in making the tests. My confidence in my approach was considerably enhanced by the fact that correlation with the data given in Road Note No. 4 was as good as I had obtained with tests at Southall. In my paper, only two examples are given in Figures 2 and 3, but the correlation was equally good for other mix proportions and water/cement ratios included in Road Note No. 4. In his contribution, Mr Murphy has also obtained satisfactory agreement with my formula in tests made at the Cement and Concrete Association.

The reason for the scatter and the discrepancy between the results Mr Teychenné has obtained and all these other results lies, I think, in his use of dry aggregate without preliminary soaking, followed by measurement of the compacting factor 10 min after mixing. As a result, the effective water/cement ratio, in so far as workability is concerned, is somewhere intermediate between the total water/cement ratio and that modified to allow for complete absorption by the aggregate.

Mr Newman has shown ⁽¹⁹⁾ that Thames Valley aggregate absorbs in 10 min roughly 60 to 80% of the maximum absorption capacity at 24 h. He further states that "from the strength results, it is apparent that the coating of cement paste slows down the rate of absorption in concrete mixes". I share his view on this.

In tests on one batch of Thames Valley aggregate, I have obtained the following values for the absorption of four different gradings, expressed as a percentage of the absorption capacity at 24 h.

Particle size	10 min	30 min
¾ in.—⅜ in.	71	89
⅜ in.—⅜ in.	96	97
⅜ in.—No. 7	83	92
No. 7—No. 100 (fairly well graded)	82	91

Whilst absorptions at 24 h were generally of the same order as were obtained by Mr Newman, it will be noted that the rate of absorption changes with particle size. The rate of absorption also varies between different samples of aggregate obtained at different times.

I think the scatter which Mr Teychenné has obtained is attributable mainly to the following.

- (1) The change in rate of absorption with particle size affects the average rate of absorption according to the combined grading of the aggregate, so that the effective water/cement ratio is also affected.
- (2) The rate of absorption of water by the aggregate in the presence of cement paste may be affected by both the water/cement ratio and the mix proportions.
- (3) Some gradings as, for instance, gap gradings with fine sand are sensitive to quite small changes in water/cement ratio. Likewise, the richer the mix, the smaller the change in water/cement ratio needed to alter the workability from low to high. Figures IV and V suggest that there is greater scatter for the richer mixes.

In order to overcome this difficulty of absorption of water by the aggregate, I consider it essential to begin mixing with a saturated aggregate. In my tests, I added sufficient water to bring the aggregate to a saturated, surface-dry condition half-an-hour before adding the cement, as is stated in the paper. This was a practical compromise arising from the evidence available when the tests were done, which suggested that the absorption by the aggregate would be almost complete in that time. The effective water/cement ratio may then be taken as the added water. Mr Newman's comment that air-dry aggregates must be completely immersed to obtain complete saturation is worth noting.

I cannot agree with Mr Teychenné that the difference between the Building Research Station results and mine is due to the fact that the values of the surface index do not reflect the relative importance of different size fractions in the grading of the aggregate. As indicated in my reply to Mr Akroyd, I consider that the surface index provides a compromise between the influences of surface area, and other factors such as frictional resistance and particle interference. My approach is, of course, empirical and further research may sort out the relative influences of these other factors.

Mr Newman comments on the limitations of the compacting factor apparatus in providing a measure of workability. He mentions mobility and stability. One might add ease of finishing (as, for instance, in roadwork) and possibly other desirable properties. I have used the compacting factor as a measure because it has seemed to me the most useful and practicable single test providing a guide to workability for the type of concrete mix widely used in practice. I agree with him that a single test method giving a better assessment of all the desirable properties will be a

most useful advance. Maybe the relation I have established will, with suitable modification of constants, be adaptable to other forms of test.

I agree with Mr Newman that the surface index may not apply to dry harsh mixes designed specifically for vibratory methods of compaction. In view of the amount of testing involved, it was necessary for me to restrict my attention to those concrete mixes in general use. I believe that 90 to 95% of the concrete produced in this country comes within the range of mixes quoted in the paper, and within a compacting factor range of 0.8 to 0.95+. I agree that high water/cement ratios, in conjunction with high cement contents, in equation 5 produce a calculated compacting factor greater than 1. I had taken the view that the straight-line relation did not hold for compacting factors above about 0.95, as indicated by the dotted lines in Figures 2 and 3, which should eventually become tangential to the line for a compacting factor of unity.

The compacting factor was calculated on the basis of saturated aggregates.

Mr Newman is correct in assuming that I used an effective water/cement ratio of 0.55, whereas A. J. Newman and Teychenné⁽⁹⁾ used a total water/cement ratio of 0.55. However, I believe their compacting factor tests were made immediately after mixing, so that the absorption by the aggregate may have been quite small. At that stage it would, in addition, be varying rapidly.

Messrs Newman and Murphy refer to the consistence of the cement and Mr Newman has emphasized the difference between ordinary Portland, rapid-hardening and high alumina cements. Mr Murphy has given most useful evidence of the influence of the cement consistence on workability. My original tests had indicated values for what he has termed s_c varying between 0.23 and 0.265 for ordinary Portland cement. With these values, the error in assuming 0.25 in a formula intended for practical use did not appear likely to be serious. However, I have since obtained values up to 0.29 and, as Mr Murphy has shown, this variation can be quite significant. The question of the best cement consistence value to adopt as an average when no actual value is available appears to be a matter which requires further investigation. As Mr Murphy states, this may result in some modification of the constant of 0.67 in the formula.

The tests in Figure 3 appear to give a reasonable correlation, except for the $\frac{3}{8}$ in. maximum grading with only 30% sand. It seems to me this would give a value of f_s of only a little over 0.60 and, whilst I have little evidence of $\frac{3}{8}$ in. maximum size aggregates, I would suspect that there are insufficient fines to fill the voids in the $\frac{3}{8}$ in. - $\frac{1}{8}$ in. material. As will be noted in the paper, I have suggested that the desirable value for f_s is 0.70 when a $\frac{3}{8}$ in. maximum size aggregate is used. The suggestion that an excess of any given size may upset the relation is possibly true, although I

think another explanation under (1) below may fit the case. A number of the mixes in Table 6 of my paper might also be regarded as coming within this category. It is well known in the soil mechanics field that single-size sands become "quick" with a small change in water content, when loaded or vibrated. I think some concrete mixes are analogous, with two results.

- (1) The variation in compacting factor which can occur with a change in effective water/cement ratio of only 0.01-0.02 is such that, even under test conditions, it is difficult to obtain reliable results.
- (2) Control of workability of such mixes is, in practice, extremely difficult. They are, in fact, only suitable for dry concrete, and then need heavy vibration to bring them to a "quick" or mobile condition.

Referring to the method of obtaining values from the computer analysis I can only say that, the analysis having been fitted to a suitable programme, the information was fed into the computer and the values indicated by the crosses in Figure 1 came out. As indicated in my reply to Mr Akroyd, the individual values do not appear to me to be critical.

Messrs Teychenné, Newman and Murphy ask for information on the suggested target values for f_s for the different maximum sizes of aggregate. These are a compromise, since it will be evident that, in theory, the lower the value of f_s the greater will be the compacting factor for any given mix. On the other hand, lack of fines seriously increases the risk of segregation and honeycombing. My observations suggested that the risk became serious below about $f_s = 0.5$ for a $\frac{3}{4}$ in. max. diameter mix, and rather less for a mix of $1\frac{1}{2}$ in. max. size below roughly $f_s = 0.45$. It is also necessary to provide a margin which will allow for the variations in grading, particularly of the sand, which inevitably occur in practice. I have therefore selected a value in each case which I feel to be about the best compromise. I have suggested a maximum value for f_s of about 0.8 for $\frac{3}{4}$ in. maximum sized aggregate.

I have no evidence within the range of mixes tested, i.e. 1:3½ to 1:8 by weight, that there is a need to change the surface index to provide more sand in leaner mixes. Within this range, the influence of mix proportions on sand content is, I think, of minor significance compared with the provision which needs to be made in practice for variations in grading. However, Mr Murphy has made an interesting suggestion for the determination of the optimum value for f_s . The formulae 6, 7 and 8 he gives would appear to give values of the same order as those I have suggested in my paper, although he does qualify them in the following paragraph. Any detrimental effect resulting from a slight excess of fines is far less than that resulting from a deficiency so that, when in doubt, I would prefer to take a somewhat higher figure for f_s , rather than aim at a minimum. Further investigation of this question is necessary.

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