Mix design for concrete block paving

by A.J. Dowson
S. Marshall & Sons Ltd, UK

Introduction
IT may seem surprising that there is scope for a paper on the principles of mix design at a time when concrete has been used as a material for concrete block paving for over 50 years. The writer has been aware of many of these principles for a long time, but it is only in the last few years that engineers and producers have taken a more active interest in the use of this type of product and there has even been a demand for the principles of mix design to be included in this conference.

The change has come about with the development of equipment designed to improve the uniformity of concrete and the realization of the benefits from this control. Concrete technology has developed differently in different countries and there are many ways of approaching the problem but this paper deals with an approach based on both experience and engineering points of views.

Background to mix design
Mix design can be regarded as the process of selection of the proportion of the different constituents of concrete to produce a product of the required quality.

In the past the mix design has been as simple as possible and the concrete quality and mix proportion were regarded as being synonymous. It has been found that the quality of concrete assessed in compressive strength terms is far from being constant. There is a tendency to change specification, so that, instead of stating the mix proportions, only the required properties of the concrete are given.

This method of specifying gives the manufacturer complete autonomy in the selection of the raw materials for the best use of available supplies of aggregate.

Mix design becomes an important part of the compliance with specifications and should be worked out in conjunction with an appropriate degree of quality control.

Outline of mix design
The purpose of mix design is to select the most economical proportions of each of the available materials to produce a hardened concrete block of the required minimum quality.

The cost of the paving block will depend on the variations in the strength which is likely to be obtained and if the range of variations is reduced, then the costs of the material will be lower.

The degree of quality control used is an essential preliminary to the selection of suitable mix proportions and this degree of control must be economically justified.

The basic problem of mix design, is to obtain adequate quality in the hardened form and sufficient workability and cohesiveness of the plastic concrete with as lean a mix as possible.

Generalising, the compressive strength and durability of concrete of given proportions, manufactured with a particular cement, improve with the reduction in the proportion of water to cement, but at the same time, the workability decreases. On the other hand, to increase the water cement proportion increases workability and cohesiveness, but reduces compressive strength.

In conventional concrete it is possible to increase the cement content by altering gradings, but, because we are using machinery to compact the concrete, this nullifies any departure from the accepted mix. Adding more cement to the mix does not increase the compressive strength.

Properties of concrete
The most important properties of concrete are its compresive strength and durability in the hardened state and its workability and cohesiveness in the plastic state. The fundamental problem of mix design is the relationship between these properties and the characteristics of the mix, and this, naturally governs the procedure for selecting the mix proportions.

1. *Compressive strength*
The rate of gain of compressive strength of concrete of given proportions varies with the type of cement and with the curing temperature; these conditions are normally determined for a particular mix design.

In all cases of mix design, we assume the concrete to be fully compacted. The compressive strength can be directly related to the water cement ratio.

2. *Durability*
The resistance of concrete to attack by weathering or chemical action depends on there being adequate resistance to the penetration of water, or any other solution, into the material because the attack is not confined on the surface. Durability is, therefore, improved by reducing the pores in the concrete; this is achieved by having a low water cement ratio and the concrete fully compacted.

3. *Workability*
The workability is affected by the water cement ratio and cement content, the shape, texture, maximum size and the particle distribution of the aggregate.

4. *Cohesiveness*
Cohesiveness is required to prevent the mix falling apart and to reduce the possibility of segregation of the coarse and fine particles during handling.

In the type of mix we use, there is insufficient water to wet the cement particles adequately, so the cohesiveness is low. However, by increasing the fineness of the particles this property is improved. The largest contribution comes from the cement itself. Also, cohesiveness depends on the shape and texture of the aggregate particles; higher for those which are smooth and round, than those which are rough and angular. Certain chemical additions to the concrete mix improve the cohesion.

Definitions

Water/cement ratio
It is generally agreed that the calculation of the water cement ratio is the ratio of the total water to the cement. The total water is the weight of water contained in the aggregate as well as the water added at the mixer.

Aggregate/cement ratio
This is the proportion of the aggregates in the mix divided by the cement proportion: in most cases this will be by weight.

Compressive strength
This is a value determined by dividing the maximum load the unit can withstand by the area under the load. To standardize methods of test, certain conditioning procedures are in use, as in BS 1881 or Interpave Specification.

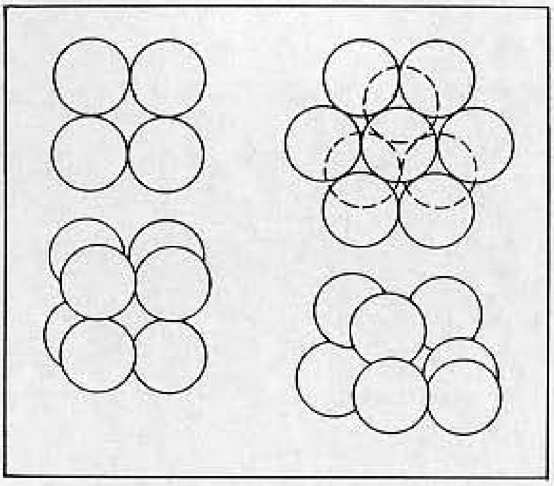
The development and considerations for methods of designing mixes for concrete block paving
At the present time, there are two general methods of manufacture of

Top left. Figure 1: Square (or loose) packing of spheres.

Top right. Figure 2: Triangular (or close) packing of spheres.

Bottom left. Figure 3: Cube packing of spheres.

Bottom right. Figure 4: Three-dimensional close packing of spheres.



concrete block paving used in this country:

1. Pressure only.
2. High frequency vibration.

Both of these methods rely on the particles of the aggregate and cement packing together in such a way as to remain together after the compaction.

This is the principle of the design method presented in this paper.

Packing of particles

As it is impossible to discuss packing of fragments of all the various shapes, let us consider the idealized spheres of material.

Firstly, arranging the spheres in a layer in such a way that each touches its neighbour; this is two dimensional packing and there are two contrasting ways of packing, square as in Figure 1 and triangular as in Figure 2. In the first case the voids are situated between four spheres, and in the second case between three spheres. In both cases, they are stacked in such a way that the spheres of the upper layer are exactly above the spheres in the lower layer. In the case of square packing of layers, we obtain cube packing of spheres in three dimensions Figure 3. In the stacking of triangular layers of spheres we get a hexagonal prismatic three dimensional structure. If the upper sphere layer is stacked with a sphere fitting into a void, in the second case, the most closely packed arrangement of spheres of equal diameter is obtained. This is referred to as "close packing" of spheres (Figure 4).

In all of these varying problems of three dimensional packing of spheres of equal diameter, great importance must be attached to the relative volume of the space between the spheres. Calculations show that, in the case of loose packing as in Figure 3, the void is 47.64%, and in the case of close packing (Figure 4), the void is 25.95%.

There is a relationship between the total surface of the sphere and the

TABLE 1

Packing configuration	*CN*	*DC*
Close	12	1.00
Cube	8	0.732
Octahedron	6	0.414
Tetrahedron	4	0.225
Triangle	3	0.155

volume of the same aggregate, and this relationship is the Specific surface.

$$\text{Specific surface} = \frac{\text{Surface area of the sphere}}{\text{Volume of the sphere}}$$

$$= \frac{\pi d^2}{\pi d^3/6}$$

$$= 6/d$$

Knowing this relationship, assuming a certain pattern of packing and knowing the average diameter of the sphere, we can easily calculate the specific surface of the aggregate. This approach has a limited application to naturally-occurring sand, because it is usually made up of grain sizes and is more complex than the original approach.

Examining the environment of any one sphere in the close packing arrangement (Figure 2), we can see that each sphere is closely touching six spheres in its own layer, three above and three below; a total of twelve spheres. The co-ordination number (CN) of a sphere is shown to be 12. Consider eight spheres centred in the corners of a cube, all touching each other as in Figure 3. Place another sphere in the centre of the cube touching all eight spheres and it is found that, using the previous

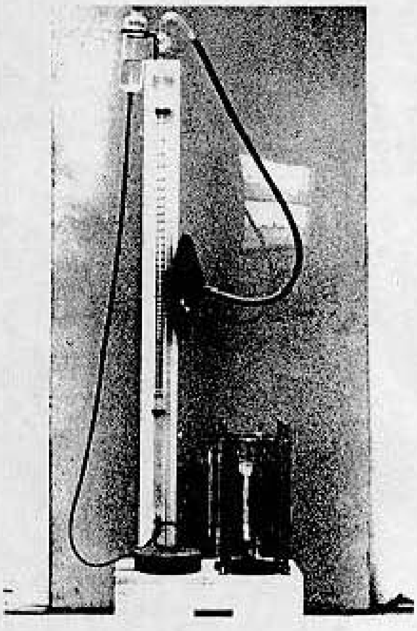


Figure 5: Apparatus.

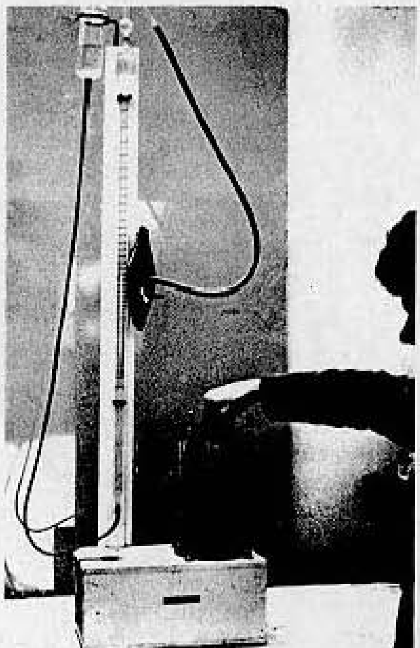


Figure 6: Compacting aggregate.

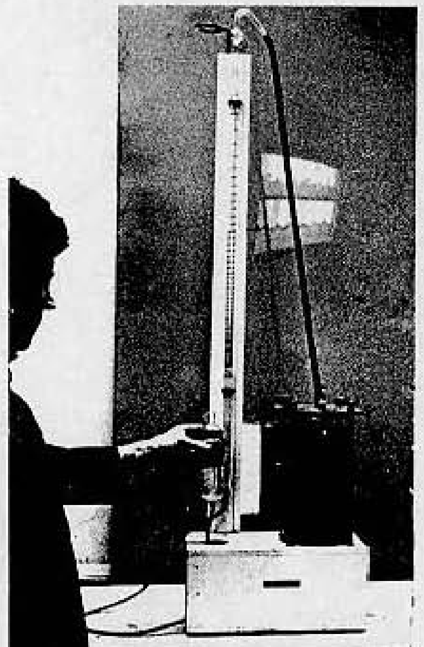


Figure 7: Testing for void.

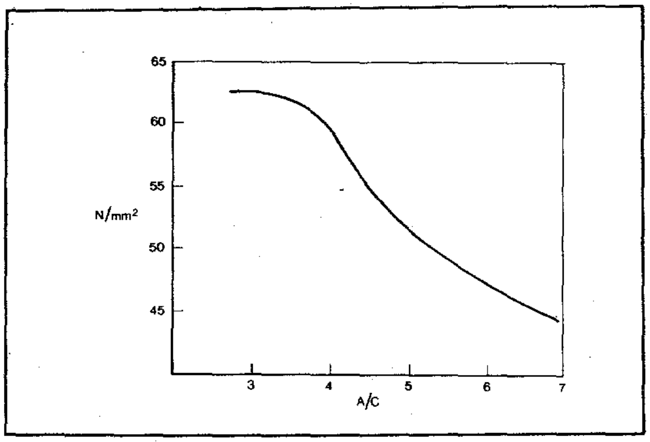


Figure 8: Effect of adding more cement.

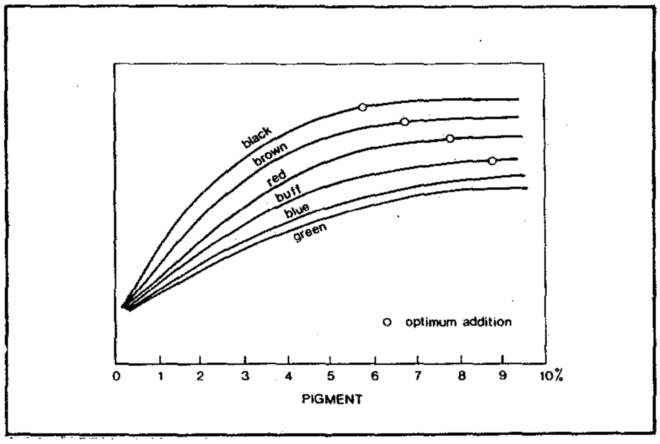


Figure 9: Optimum pigment levels, based on cement weight.

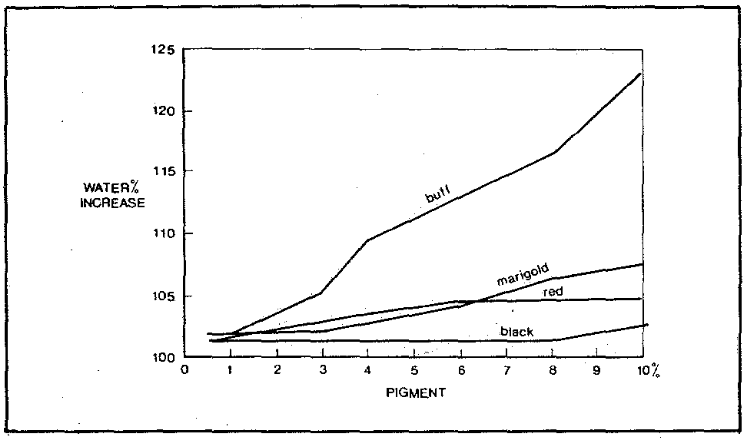


Figure 10: Water demand of different colours.

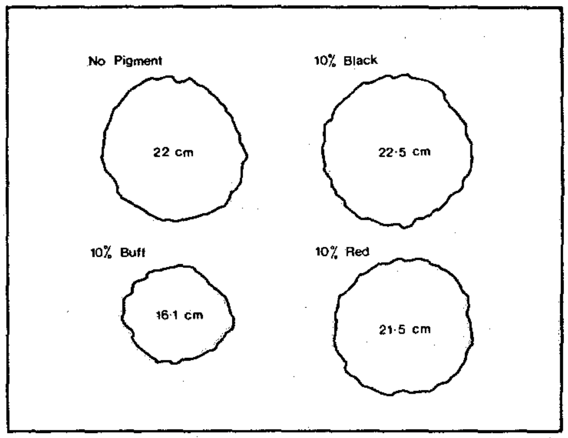


Figure 11: Workability as indicated by spread.

example, the co-ordination number is 8. Mathematically, the diameter of this central sphere is approximately three quarters of the surrounding spheres. Proceeding further, we can calculate the co-ordination number and the diameter of the central sphere (DC) for a number of simple configurations (Table 1).

This table clearly shows that the smaller the co-ordination number, the smaller is the space between spheres.

Such considerations, here touched on only lightly, may help in the explanation of the complexity of the packing of grains of unequal sizes.

Measurement of voids

The void content in a granular material, whose specific gravity is known and is consistent throughout the sample, is easily calculated from measurement of the bulk density.

BS 812 gives the laboratory procedure for determining the specific gravity and voids, but this can take several days to complete.

A simple method by which the void content can be measured is to measure the volume of water that can be poured into a container of known volume and already filled with the combined aggregates, but this method is inaccurate because of entrappment of air, porosity and bulking. A method has been developed by the Building Research Station and marketed by Jenconcs (Scientific) Ltd, and Figure 5 illustrates the apparatus. The principles involved are that the opening of the tap allows the column of water in the measuring tube to act on the total volume of air within the apparatus (the volume of air samples plus the volume of air from the top of the sample to the water level in the glass bulb) causing an increase in volume and a corresponding decrease in pressure. Equilibrium of the water column is reached when the pressure of the air in the system plus the pressure due to the height of the water column is equal to the atmospheric pressure. As the volume of air above the sample is constant, variations in the distance that the column falls is directly related to the volume of air in the sample.

Method of measuring void content

The material is placed in the sample container, being packed in a manner appropriate to that for which the void content is required (Figure 6). The top is placed on the container and sealed, the air release tap being open to atmosphere at this stage.

The air release tap is then closed and the levelling bulb lifted from its top position and placed in its position in the hole provided in the box (Figure 7). This allows the water to flow from the measuring tube until it is held at the point indicating the percentage void content of the samples. The measuring process may be repeated several times to obtain a clear mean value and eliminate the chance of a faulty reading.

Factors affecting mix design procedures

(a) Cement content

As the process relies on low workability, the existing water in the mix is barely sufficient to hydrate fully the cement. Further addition of cement has the effect of lowering the workability and, because of the lack of water, the cement acts as a filler and reduces the strength (Figure 8).

(b) Pigments

1. CONCENTRATIONS. As with all methods of colouring material, there is an optimum concentration for maximum intensity (Figure 9).

2. WATER DEMAND. Due to the particle shape of the pigment, different colours require different water contents (Figure 10).

If the water cement ratio is constant then it is possible to measure the workability by measuring the spread of the concrete (Figure 11).

Alternatively. Figure 12 illustrates the strength effect of pigment concentrations at a constant water cement ratio.

(c) Cement
In the UK, cement quality is controlled by BS 12 and all manufacturers exceed the minimum limits specified.

(d) Aggregates
Properties of aggregates can affect the various properties of concrete and this section of the paper discusses the importance of the aggregates in controlling those properties. Those properties of the aggregate which have the most important influence on the quality of concrete are the cleanliness, the shape and surface texture, and the grading.

(i) CLEANLINESS
All aggregates should be free from unwanted material (whether it be fine particles or chemical impurities which can affect the hydration of cement) and from particles of the wrong size of material.

It is essential that the fine aggregate does not contain more than 25% acid soluble material on that fraction retained or passing the 600 micron sieve.

This material affects the resistance to polishing and special care must be taken with sea dredged aggregate containing shell.

(ii) SHAPE AND TEXTURE
The surface characteristics of aggregate particles of all sizes have an important influence on the properties of the fresh concrete and on the compressive strength of high strength concrete.

For machine orientated production used for the manufacture of concrete paving blocks, the aggregate should be naturally occurring, rounded and smooth textured or alternatively angular or cubical.

(e) Effect of density on strength and absorption
As with all good mix design, the object is to compact fully and to achieve the maximum density. (The density of fully-compacted concrete is dependent on the density of the aggregate used). Figure 13 shows the effect of lowering the density and this was obtained by adjustment to the machine. All the blocks were compacted fully.

(f) Effect of water content on strength
Using the two parameters dictated by the machine (the minimum water and maximum water content) the effect on different types of aggregates with different cement content is shown in Table 2.

TABLE 2:

Aggregate type	*Cement content kg/mm²*	*% Moisture content*	*Mean strength N/mm²*
Natural sand	456	5.9	57.9
and	570	6.1	69.0
Gravel	570	7.1	67.5
Sand	380	5.2	53
and	380	7.0	53.5
Granite	456	5.0	55
	456	6.8	56
	570	5.2	61
	570	6.9	67
	456	6.9	55.5
Granite	570	5.4	59.0
	570	6.9	62.0

(g) Effect of water content on durability
Using the previous conditions, blocks were tested under the RILEM regime and the results are shown in Table 3. The weight loss has been recorded for every ten cycles in Table 3. The twenty-fifth and fiftieth results are shown.

TABLE 3: Freeze thaw

Aggregate type	*Strength*	*% Moisture*	*Cement content*	*Weight loss mg/mm²*	
				25 cycle	*50 cycle*
Gravel	52.5	6.1	570	0.102	0.188
and	57.0	7.1	570	0.103	0.188
Sand	51.5	6.0	456	0.520	0.989
	48.5	5.9	456	0.193	—
Sand	51.5	5.2	570	0.135	0.219
and	57.0	6.9	570	0.135	0.202
Granite	46.5	5.0	456	0.115	0.169
	47.5	5.8	456	0.183	0.284
	45.0	5.2	380	0.110	1.191
	45.0	7.0	380	0.195	0.336
	50.0	5.4	570	0.095	0.149
Granite	52.5	6.9	570	0.073	0.161
	47.0	6.9	456	0.132	1.272

(h) Curing regime and conditions
Curing the concrete paving block is essential to maintain the quality required, and the principles are similar to the curing of conventional concrete. Curing can be categorized into two main types – one is natural air curing and the second is accelerated curing.

As stated previously, there is insufficient water in the mix to hydrate the cement fully and it is found that if this type of concrete is cured using moisture and slightly elevated temperatures, the early as well as the 28 day strength is higher compared with natural curing. Steam curing can be used, and at one day the strengths are increased, but the 28 day strength can be 20% lower than naturally cured blocks. Although it is impossible to control the curing of the blocks once they are stacked in the storage area, Figure 14 shows the effect of different types of conditions.

(j) Partial substitutes for cement
There are several materials which can be used to replace part of the cement. These are naturally occurring pozzolans and artificial pozzolans, blast furnace slag and chemicals.

ARTIFICIAL POZZOLANS
Pulverised fuel ash (PFA) is a by-product of the electricity generating industry and is largely a siliceous material which can improve some of

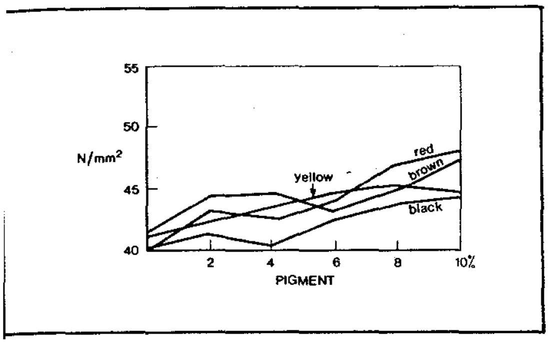


Figure 12; Strength effect of pigmernts at constant water: cement ratio.

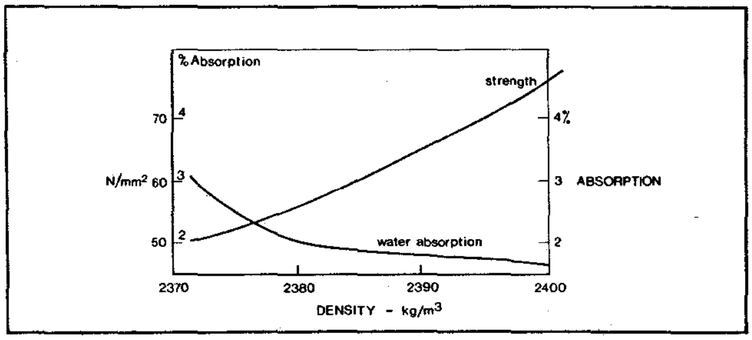


Figure 13: Effect of lowering the density.

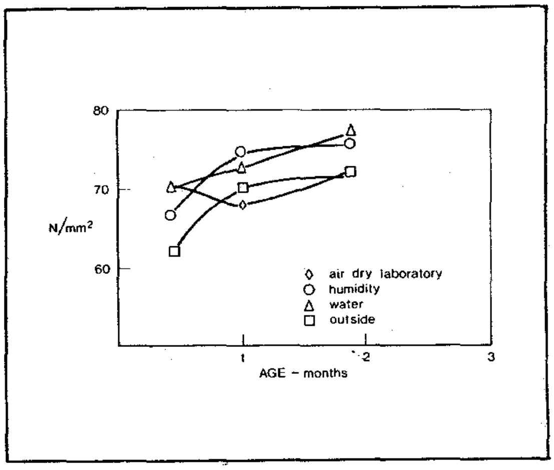


Figure 14: Effect of storage conditions on strength.

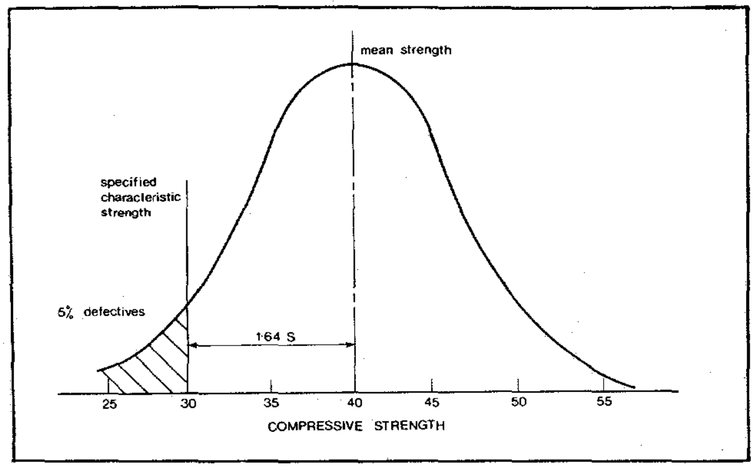


Figure 15: Distribution of results.

the properties of both the plastic and hardened state of concrete, as well as imparting other desirable properties, not normally present in ordinary Portland cement. Pozzolan reacts more quickly at enhanced temperatures, and is therefore of most benefit with some form of heat curing; it also contributes, under normal conditions, to strength improvement at later ages.

BLAST FURNACE SLAG

Blast furnace slag is a by-product of the manufacture of pig iron in a blast furnace and is formed by the combination of silica and alumina etc. with limestone flux. Its essential components are the same oxides as are present in Portland cement but in differing proportions.

NATURALLY-OCCURRING POZZOLANS

Naturally-occurring pozzolans occur in the volcanic areas and trasses of Italy, Germany and Greece. The diatomaceous earths of Scotland and Scandinavia, from the skeletons of diatoms, are sometimes known as moler.

CHEMICAL

The use of admixtures has been widespread in the manufacture of conventional concrete throughout the world. In the semi-dry process, several UK companies have developed systems that combine a plasticiser and air entraining agents, which enables reductions of cement.

Table 4 illustrates the partial replacement of cement using PFA and an admixture.

Method of designing mixes for concrete paving blocks

Although this recommended procedure for designing mixes for paving blocks has been simplified as far as possible, the experience of the designer plays a large part in the skill of selecting materials based on his experience on the principles governing the properties of concrete.

The problem of the design of a mix for a given purpose may be reduced, in its simplest form, to the question of obtaining concrete of the required strength and workability at the lowest cost by a suitable choice of materials and of the proportions in which they are used.

The figures and curves provide a means of arriving at a reasonably satisfactory and economical choice of proportions.

TABLE 4: PFA

Cement	*PFA*	*Av. strength*
100%	—	60
75%	25%	60
64%	36%	59

Chemical

Control	62.8
10% reduction in cement	60.4

Compressive strength

The strength development by a concrete of given materials and proportions increases for many months under favourable conditions, but in the majority of specifications the strength at 28 days is specified. Because of variability of concrete strength, the mix must be designed to have a considerably higher mean strength than the strength specified.

Characteristic strength is now replacing the older concept of minimum strength. The difference between the specified characteristic strength and the target mean strength is called the "margin".

This margin is based on knowledge of the variability of the concrete strength from previous production data, expressed as a standard deviation; or alternatively, a substantial margin is applied until an adequate number of results is obtained. The overall variation factors can be considered to be made up from:

1. Variation in the quality of material used.
2. Variation in the mix proportions in the batching process.
3. Variation due to sampling and testing.

The distribution of results is now

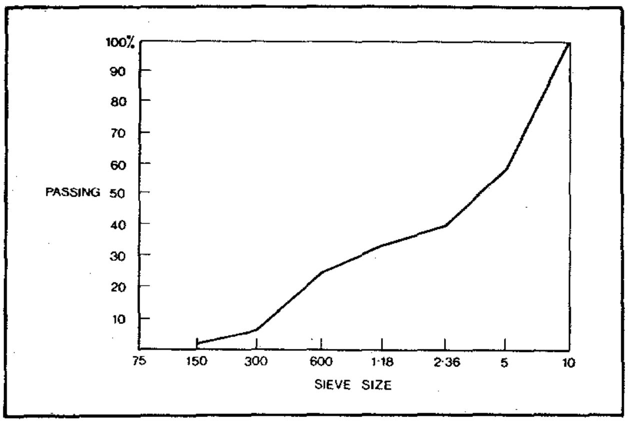


Figure 16: Aggregate grading curve.

generally accepted to follow the curve shown in Figure 15. This is the normal distribution curve and it has a precise mathematical equation. The area under the curve represents the total number of results, and the proportion of results less than some specified value is represented by the area beneath the curve to the left hand side of a vertical line drawn through the specified value.

Standard deviation (SD) is a measure of the variability and is calculated from the formula:

$$s = \sqrt{\frac{\in (x—m)^2}{n—1}}$$

where x = individual results
n = number of results
m = the mean of the n results

Characteristic strength
There is always a possibility, however remote, that a result will be obtained less than the specified strength. The current practice is to quote characteristic strength as a means of specifying the quality of concrete below which a specified proportion of results may be expected to fall.

Characteristic strength
= Average strength — (k x SD)

Where k = a constant for defective products.

SD = Standard Deviation
For concrete paving blocks

k = 1.64 which represent 5% defectives

SD — Where no results are available.
Pressure type machine, small number per cycle = 3.5 N/mm²

Vibration, large number blocks per cycle = 7.0 N/mm²

Selection of water contents
As previously stated, the machine is the governing factor in the choice of the water content, and this normally lies between 5 and 7% moisture of the total mix weight.

Cement content
With the relatively high strength requirement in the UK the aggregate cement ratio will be in the range of 3:1 to 6:1. A typical curve of strength to cement content is shown in Figure 8 and an approximate value is obtained after calculating the Target or Characteristic strength.

Gradings
The aggregate should be chosen and combined if necessary to fit as closely as possible to the curve of Figure 16. The curve is designed to give a close textured surface but, by increasing the coarse content of the mix, a more open textured appearance is produced.

The curve has been obtained by using the void meter to determine the lowest possible percentage of air voids for a wide range of aggregates, and has been confirmed by a large number of sieve analyses taken from production units all over Europe.

Analysis of the particle size distribution
There are several ways of measuring the partical size distribution and the most common is by sieve analysis. The exact method of procedure is described in BS 812 Part 1 1975, but a brief description is given below.

A representative sample of material is taken and reduced to the appropriate minimum mass and brought to a dry condition before weighing and sieving. The sample of dry material is weighed and sieved successively on the appropriate sieves starting with the coarsest. (The sieves must be dry and clean before use).

After shaking each sieve for not less than two minutes, the material retained on each sieve, together with any material cleaned from the mesh, is weighed.

The results are calculated and reported as either:

(a) The cumulative percentage of the mass of the total sample passing each of the sieves.
or
(b) The percentage of the mass of the total sample passing one sieve and retained on the next smaller sieve.

Methods of combining aggregates
The availability of aggregate for use in the manufacture of concrete paving blocks necessitates the blending of two or more aggregates to achieve the required gradings used in this mix design method. To do this,

TABLE 5: Example showing combining of two aggregates

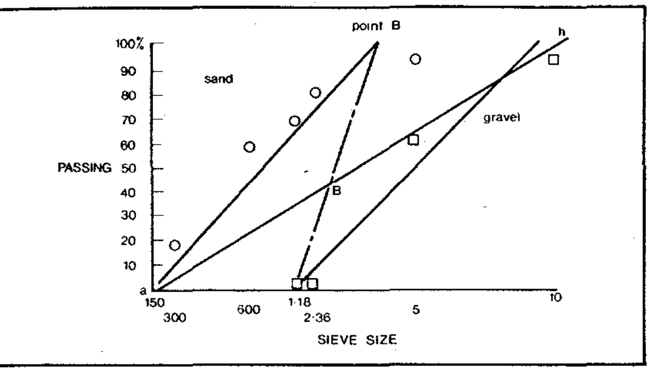
Range of sieve sizes	*Surface area index*	*Grading % between sieves*			*Surface area indices*		
		Required	*Coarse*	*Fine*	*Required*	*Coarse*	*Fine*
38 to 19 mm	1	3			3		
19 to 10 mm	2	27	58		54	116	
10 to 5 mm	4	12	40		48	160	
5 to 2.36 mm	8	9	2	3	72	16	24
2.36 to 1.18 mm	16	8		16	128		256
1.18 mm to 600 µm	32	10		23	320		736
600 to 300 µm	64	18		46	832		2944
Passing 300µm	128	13		12	1664		1536
		Total			3121	292	5496
		Surface area index			31.21	2.92	54.96

Let X be % of fine material to be used, then the coarse and fine aggregate are combined to have the same surface ara index:—

$$2.92\,(100 - X) + 54.96 = 31.21 \times 100$$

$$. . X = 49.0$$

So ratio of fine aggregate to coarse is 49/50



'igure 17: Graphical method 1.

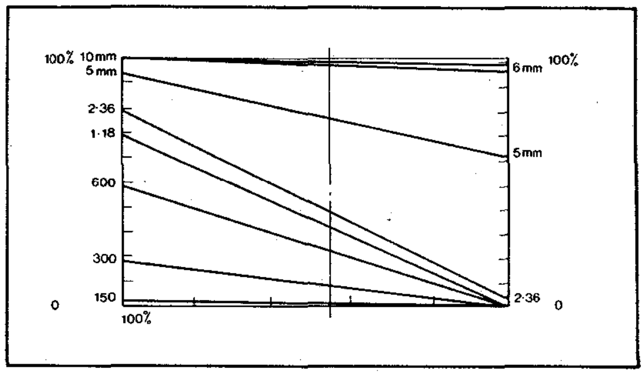


Figure 18: Graphical method 2.

here are several methods, and ıppended below are the methods nost commonly used.

Graphical method 1. (Figure 17)
Rectangular co-ordinates are set up vith a scale of percentage passing 0 to 100%) vertically, and a straight ine a–h drawn through the origin at ıny convenient slope. Vertical lines ıre drawn through the points a–h vhere the lines a–h intersect the horizontal lines, corresponding to he values of the percentage of naterial required to pass the various sieves according to the required grading; these lines are the co-ordinates for the sieve sizes and are narked accordingly. The values of he actual percentage passing each sieve are then plotted for each separate aggregate, and the steepest reasonable line is drawn through each set of points. A straight line is drawn between the points where the finest aggregate cuts the 100% and he next finest aggregate cuts the 0%. Similarly, a straight line is drawn for he coarse aggregate.

The values of percentage passing, corresponding to the intersections of he straight lines with the original a–h ine, are recorded and indicate the proportions in which the aggregates should be combined.

Graphical method 2
A piece of graph paper is marked vith percentage scales along three ides as in Figure 18. The gradings of he fine aggregate are checked off ılong the left hand vertical axis by narking points and referencing them vith a sieve size such that the ordinate of each point represents the percentage of the material passing that sieve. The grading of the coarse material is marked off along the right hand axis in a similar manner.

Each point on the left hand axis is joined by a straight line to the point with the same sieve size on the right hand axis. A vertical line is drawn through the point where the sloping line representing the 600 sieve intersects the horizontal line representing the percentage of material passing a 600 sieve required in the combined grading. The percentage of fine aggregate, as delivered, required in the total is read on the top scale, where this is intersected by the combined aggregate line.

Arithmetical method
This method is based on several assumptions but, because the actual values of specific surface are difficult to measure in practice, the calculations are made for convenience using an arbitrary surface area index which doubles as the size of the material is halved, but which does not allow for variations in the shape of the aggregate particles of different sizes. Knowing the required grading and the grading of the aggregates, each sieve starts from the number for each size. To complete each percentage of the material, a particular sieve unit is cross multiplied with its appropriate surface area index. The results for the various gradings are totalled and divided by 100 to give an overall surface area index. The coarse and fine aggregate are then combined so that they have the same surface area index as the required grading. An example is shown in Table 5.

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Pozzolanic, Chester, for the supply of the pulverised fuel ash.

Chemical Building Products for the supply of the admixtures.

Bayer Chemicals for information on their pigments.

Useful sources of information

1. *Design of normal concrete mixes.* Department of Environment.
2. British Standards. British Standards Institution, 2 Park Street, London SW1.
3. *Specification for concrete block paving.* Interpave, 60 Charles Street, Leicester.
4. Concrete information. Cement & Concrete Association, Wexham Springs, Slough.
5. Admixtures. Cement Admixtures Association, 15 Tooks Court, London EC4A 1LA.
6. PFA: 1. Central Electricity Generating Board, (Ash Marketing); 2. Pozzolanic, Chester; 3. Pozament Cement Ltd, Leeds; 4. Frodingham Cement Co. Ltd, Scunthorpe.
7. Void meters. Jecon of Hemel Hempstead.