SPECIFYING FOR CONCRETE DURABILITY: PART I - A CRITICAL REVIEW

by

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Abstract

While compaction, curing, constituents and cover are the four Cs that affect concrete durability, the first two are more prone to workmanship factors, while the last two are easier to specify. Although specifying for durability by strength has probably the least relevance of the currently available methods for specifying the durability of OPC concretes, it has the greatest applicability, and its relevance can be improved by relating it to either mix proportions or performance criteria. Australian strength specifications are being related to carbonation and sorption data. In the U.K., specifying for concrete durability by strength, based on correlations with mix proportions, has largely eliminated the problems of incompatible or uneconomic specifications.

1.0 Introduction

A structural material must possess both strength and durability. While strength ensures that the structure can sustain the loads applied on it, durability is required to ensure that such strength does not decline with time.

Where concrete is concerned, the predominant current worldwide focus of attention is on its durability. While the concrete itself is prone to degradation due to causes such as sulphate attack and alkali-silica reaction, the more common durability problem is the corrosion of the steel embedded in the concrete as reinforcing bars or prestressing wires.

The durability of concrete is considered, in general, to be dependent on its permeability, since it is a permeable concrete that will allow the ingress of substances such as

(i) Sulphates, leading to sulphate attack,

(ii) Moisture, leading to the onset of mechanisms such as alkali- silica reaction and reinforcement corrosion,

(iii) Chlorides, which will promote corrosion, both by reducing the alkaline protection given to the steel by concrete and by acting as an electrolyte to reduce the resistivity of the concrete,

(iv) Oxygen, which is required for the corrosion reaction and the formation of rust, and

(v) Carbon dioxide, leading to carbonation, and a consequent reduction in the alkaline protection afforded to the steel by concrete.

Since most aggregates used for the production of concrete are dense and impermeable, the permeability of the concrete will depend on the following (1):-

(i) The Constituents used for the mix, especially the water/cement ratio, since this is considered to determine the "capillary porosity" that will contribute to permeability.

(ii) The curing of the concrete, since this will enable the cement hydration reactions to proceed and reduce the porosity of the cement paste.

(iii) The compaction of the concrete during placing, to eliminate large voids and honeycombs, caused by air entrapped during mixing.

(iv) The cover given to the embedded steel, since this will determine the path length required for external deleterious substances to reach the steel.

One further complication is that good quality concrete is required mainly in the cover zone, since it protects the

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steel. However, it is this very zone that is at a disadvantage with respect to concrete quality, because of skin effects (2). Furthermore, it is in this zone that there is the greatest difficulty in ensuring good workmanship - because it is difficult to compact concrete into the soffits and vertical faces of members through the steel reinforcement and because poor curing will cause moisture to be lost primarily from surface zones (3).

It can be seen from the preceding discussions that the overall protection to the steel given by the cover zone concrete depends on both concrete quality and thickness (i.e. the cover). Where concrete quality is concerned, there are three contributory factors - namely mix constituents, compaction and curing.

All of the above factors depend on both design and workmanship. However, curing and compaction are more dependent on workmanship factors and less easy to specify while mix constituents and cover are easier to specify though also dependent on workmanship factors (see Figure 1).

2. Specifying for Durability

There are possibly three main methods of specifying for durability at present, namely

(i) Specifying mix proportions, which would mean a maximum water/cement ratio, but in some cases, for easier control, a minimum cement content.

(ii) Specifying a cube strength or cylinder strength to be achieved at a given age - generally 28 days - after water curing (i.e. the grade of concrete).

(iii) Specifying performance criteria for the completed structure, which may involve measures of water absorption or air permeability.

Each of these methods must be evaluated with respect to its <u>applicability</u> and <u>relevance</u>. Applicability has to do with how easily a test can be performed and the acceptability of the result. Relevance has to do with how close the method or test is to characterising the durability of the concrete.

Specifying by strength has a high degree of applicability. It involves a test that is easily performed, and the concrete grade has become a widely accepted measure of its strength properties. However its relevance for durability is questionable. On the one hand, it does not measure the quality of the concrete in the structure itself and is thus unable to account for the workmanship factors of curing and compaction. Furthermore, even its ability to predict the "potential durability" of a given mix is suspect. Where there are variations in cement type, involving blended cements, strength may be a better measure of durability than mix proportions (4); however where there are variations in Ordinary Portland Cement, specifying by mix proportions may be more appropriate (5). This is discussed more fully in Section 3.

Specifying by performance criteria has a high degree of relevance, since the tests will be performed on the completed structure, and will reflect the effect of all the factors that influence the final durability of the concrete in the structure, including the workmanship factors. The site tests that have been developed to date are all permeability tests (6), and permeability is arguably the best indication of durability. However, permeability tests on structures are very difficult to perform and results are very sensitive to the moisture level in the concrete (7). Furthermore, these tests are relatively new, and it will take a considerable time for them to gain acceptance. Hence the applicability of this method is low.

Specifying by mix proportion suffers from the same lack of relevance that the strength method does, in that it does not reflect the durability of the concrete in the structure itself. However at least where different Ordinary Portland Cements (OPCs) are concerned, specifying a maximum water/cement ratio and/or a minimum cement content will probably give a better measure of "potential durability" than the concrete grade (1,5). Hence, the relevance of this method is average but probably a little better than that of specifying by strength. The degree of applicability of this method is also low to average. Although the water/cement ratio of a mix may be difficult to control, the cement content can be fairly easily controlled. However, there is no easy and accurate method of checking the mix proportions after mixing; one has to resort to chemical analysis of hardened concrete (which is difficult to perform routinely) (8) or wet analysis of fresh concrete (which is not in common usage and not very accurate either) (9).

The above ideas regarding the applicability and relevance of the three methods of specifying for durability are depicted graphically in Figure 2. If equal weight is given to both applicability and relevance, it seems that specifying by strength is the best method. Its applicability is excellent; furthermore, there can be steps taken to improve its relevance.

The relevance of the strength method can be improved if the value of strength specified is related to an entity that has greater relevance - i.e. the mix proportions, or better still, the performance criteria. U.K. (10) and Australian

(11) attempts to do so (See Figure 3) have been described in the literature, and are reviewed below.

3. From Mix Proportions to Strength: The U.K. Example

3.1 The CP 110 Approach

The CP 110:1972 (12) method of specifying durability was by a maximum water/cement ratio and/or a minimum cement content to ensure quality, and a cover requirement based on the grade of concrete. These values were varied, of course, for different exposure conditions.

However, since there was no attempt to guide the designer to choose a grade of concrete corresponding to the mix proportion requirements, the specifications could sometimes become conflicting, resulting in impossible or uneconomic situations (10).

This is depicted schematically in Figure 4, where a mix is specified by a characteristic strength of 20 N/mm^2, a minimum cement content of 230 kg/m^3 and a maximum water/cement ratio of 0.65. It is only if the starting point is the third of the above specifications that the other two are satisfied, and here too the characteristic strength obtained is 30 N/mm^2, which may result in a loss of economy if the structural design had previously been carried out for a characteristic strength of 20 N/mm^2.

Meanwhile, it was also noted that cement quality had been changing with time, leading to higher strength concrete, since the percentage of C_3S in cement had increased at the expense of the C_2S percentage (5,13) and also because modern grinding mills produced cements of narrower particle size distribution (14). This meant that the given 28 day strength could be achieved with a lower cement content and higher water/cement ratio in the 1980s than say in the 1960s or earlier (5). The extent of the variation can be seen in Figure 5.

3.2 The Strength vs. Mix Proportions Debate

There is considerable debate as to whether strength or mix proportions (primarily the water/cement ratio) is the better index for durability. The long established opinion is that water/cement ratio is better. Dhir et al. (7) demonstrated this for measures of durability obtained from in situ tests such as the ISAT and Figg test. They also found that the curing regime had a significant effect on the above results. Furthermore, they showed that specifying for durability by minimum cement content or strength grade had serious shortcomings (7,15).

Another study by Grube (16) also established the importance of good curing to reduce oxygen permeability and depth of carbonation. He also concluded that compressive strength of standard cubes was unsuitable to predict permeability and that higher design strengths based on lower water/cement ratios could compensate for poor curing to a certain extent.

On the other hand, using durability indicators such as carbonation and moisture loss upon drying, Parrott argues very convincingly for a strength index, since concretes made with a variety of cement types and water/binder ratios showed similar indicator values for similar strengths (4). In that particular investigation, he did not compare concretes with OPCs of differing quality. However, in a paper describing mathematical modelling of cement properties (17), he shows that concretes made with 1980 U.K. OPC have higher strengths and shorter curing periods to achieve a specified permeability for the same water/cement ratio than those made with 1950 U.K. OPC. Furthermore, at higher strengths (35-55 N/mm^2 at 28 days) it is seen that an equal strength criterion between 1950 and 1980 concretes results in approximately equal curing period requirements. Nevertheless, at lower strengths (25 N/mm^2 at 28 days), it is seen that the use of the equal strength criterion will result in longer curing periods for concrete made with 1980 U.K. OPC.

Ho and Lewis also report that an equal strength criterion does not give equal carbonation depths for different concrete types (11). They also show that water/cement ratio is the decisive parameter governing carbonation depth, as opposed to water/binder ratio, where blended cements are concerned (11). However, they found that equal water/cement ratios for two different OPC concretes yielded differing values of sorptivity, the higher early strength concrete faring better (11,18). The beneficial effects of water-reducing and air entraining admixtures was also demonstrated (11,18).

Ben Bassat et al. (19) have compared the effect on durability (measured by depth of carbonation, initial surface absorption and oxygen permeability) of concretes with different OPC properties - i.e C_3S contents ranging from 33.5 to 67.0 and C_3S/C_2S ratios ranging from 0.9 to 10.6 - cured either well (wet) or poorly (dry). They found that differences due to curing regime and cement composition reduced as the water/cement ratio was reduced (from 0.7 to 0.4). When using an equal water/cement ratio criterion, they found that the relative performance of concretes with the higher C_3S cements was better if dry curing was used, but that the properties were similar if wet curing was used. When using an equal 28 day strength criterion, they found that the concretes with higher C_3S cements performed slightly less well under wet curing but somewhat better under dry curing, when compared to the concretes with lower C_3S cements.

In practice, strength measurements are made on wet cured cubes at an age of 28 days, but the actual structure will not be cured to the same extent, thus adding a further complication. In this context it is interesting to note that Parrott found less scatter in his results when he correlated depth of carbonation with wet cured cube strength at the end of the curing period as opposed to 28 day wet cured cube strength (4).

The above discussion does not completely resolve the strength vs. water/cement ratio debate. However, it emphasises the need for good curing of the actual structure, whether durability is specified by water/cement ratio or by wet cured 28 day cube strength; it also suggests that concretes with higher C_3S cements will perform better in actual structures.

While the argument supporting strength as the best index for durability is based on the idea that both strength and durability are related to large diameter porosity (17), the argument supporting water/cement ratio as the best index is based on the idea that the water/cement ratio will influence porosity as well as pore connectivity, both of which are factors for permeability (1). Figure 6 gives an indication of how higher water/cement ratios can lead to greater pore connectivity, whatever the subsequent degree of hydration. In fact, steps have been taken in the new U.K. Portland Cement standard to prevent the use of high water/cement ratios in conjunction with highly reactive cements by imposing an upper strength limit for the 28 day strength of OPC, in addition to the usual minimum strength requirement (20).

There is also evidence that the strength vs. porosity relationship is influenced by the type of hydration product (21). Atzeni et al. (22) found that the compressive strength of hardened cement pastes was dependent on pore distribution and "characteristic strength" (i.e the strength value found by the extrapolation of the linear strength vs. porosity relationship to zero porosity), in addition to total porosity; they also found that macro-defects did not significantly influence compressive strength. The existence of such a "characteristic strength", which varies with cement type and water/cement ratio (22), indicates that strength depends on factors other than porosity alone; therefore strength may not be a universal indicator of permeability and durability.

3.3 The BS 8110 Approach

The problems inherent in specifying for durability according to CP 110: 1972 (12) (see Section 3.1) have been somewhat remedied in BS 8110: 1985 (23), where its Table 3.4 in Part 1 (reproduced here as Table 1) not only specifies durability by cover and grade, but also indicates that the grade specified corresponds to a minimum cement content and a maximum water/cement ratio.

The background to this table is given in the paper by Deacon and Dewar (10), who conducted a survey of U.K. batching plants to obtain strength vs. mix proportion relationships for each plant, the mix proportions being water/cement ratio and cement content. The scatter of these relationships is shown in Figure 7. In order to specify the strength which corresponded to a desired maximum water/cement ratio or minimum cement content, they chose values of strength which would satisfy the above mix proportion specifications 96% of the time.

It must be emphasised here that the index of durability used in BS 8110:1985 (23) is mix proportions. However, it has related these mix proportions to strength, which is a much easier parameter to measure and control. This is clearly evident in the provisions made in the code (23) for reducing the grade if a checking regime establishes that a lower grade of OPC concrete complies with the cement content and water/cement ratio limits. Such a relaxation of grade is not allowed, however for concretes using blended cements. It may thus be inferred that a mix proportion specification is used when comparing durabilities of concretes with different OPCs while a strength specification is used when comparing durabilities of concretes with different cement types (e.g. blended cements).

It should be noted that the draft European Standards for cement and concrete (24-26) have reverted back to specifying durability by minimum cement content and maximum water/cement ratio, as in CP 110:1972 (12), for cements of widely differing blends, without any reference to a strength criterion. This is probably due to the wide range of strengths achieved by cements across Europe. However, in the light of the previous discussion, this could result in a loss of relevance, if not safety.

4. From Performance Criteria To Strength: The Australian Example

The new Australian code of practice for concrete structures (27) specifies for durability by strength. The cover is to be varied according to the exposure condition and grade of concrete used - it should be noted that the strengths referred to in the Australian code are cylinder strengths, as opposed to cube strengths in the U.K. codes. Since some work has been done by Australian researchers on relating performance criteria to strength, this research is being used to evaluate the specifications in the standard (11,28-30). An extract from the durability recommendations of the Australian code (27) is given as Table 2.

The two performance criteria studied by Ho and Lewis (11) are carbonation and water sorptivity. Their accelerated carbonation tests are meant to give an indication as to how quickly the steel will get depassivated in a structure due to atmospheric carbon dioxide, while their water sorptivity tests are meant to give an indication as to how quickly chlorides will penetrate the cover concrete, assuming the absorption model of chloride ingress as opposed to the diffusion model (28).

The above indicators were measured by Ho and Lewis for concretes made with a wide range of cements (including blended cements), aggregates and admixtures. These specimens had a quality corresponding to 7 days of standard moist curing, which was considered to be equivalent to the average curing experienced by a structure over its service life. They also measured the standard 28 day cylinder strengths of these concretes. Finally, they estimated limiting values for carbonation rate and water sorptivity that would be required over a given cover for a design life of around 40 to 60 years in various environments. Thus, they could determine the strength of concrete required over a given cover for providing protection to the reinforcement (11). Tables 3 (a) to (d) give some idea of their approach.

The comparisons they have made with the code indicate that the code values are safe, apart for a few relatively uncommon mixes (11,29). In fact the code values may be unduly conservative in that it requires characteristic strength values which correspond to the mean strength requirements of Lewis and Ho (29).

Another Australian study by Guirguis (30) shows that calculations based on chloride diffusion as opposed to water absorption will require higher covers than those the code (27) specifies; it also shows that if carbonation data alone is considered, the required covers are again higher than code specifications for "mild" (A1) and "moderate" (A2) environments. Ho and Lewis (11) however place limits on the acceptable carbonation rate not on the basis of the carbonation front movement alone, but also on the basis of the risk of subsequent corrosion, depending on the environment concerned.

5. Discussion and Closure

Both U.K (23) and Australian (27) codes of practice specify for durability by strength, and this seems to be the best way forward. In the U.K., the code provisions have been arrived at by a nationwide survey that correlated strength with mix proportions (10), while in Australia, the code requirements are being evaluated with respect to performance criteria (11). One significant advantage in the Australian approach is that cover values are obtained directly from the correlation itself, whereas in the U.K. approach, reliance has to be placed on additional experimental or empirical evidence to arrive at cover values.

It is difficult to make comparisons between the U.K. and Australian code provisions, because their definition of exposure conditions is not identical and also because the Australian strength specifications are in cylinder as opposed to cube strengths. However, assuming that the five U.K. exposure classifications correspond approximately to the Australian ones and taking cylinder strength as being between 0.8 to 0.9 times cube strength (31), the comparison in Table 4 can be made. The U.K. provisions are given as in BS 8110 (23), but the Australian provisions are derived from AS 3600 (27) as described above, and given in parentheses. The U.K. provisions seem to be more stringent for the mild and moderate exposure conditions, while the reverse is indicated for the very severe and extreme conditions.

When thinking of making specifications for concrete durability in Sri Lanka, it is probably best to adopt the U.K approach, as we generally follow U.K codes of practice. Furthermore, much research will be required to relate strength to performance criteria. Therefore, when specifying by strength, it will be necessary to carry out batching plant surveys in Sri Lanka as was done in the U.K. (10) prior to the BS 8110 (23) recommendations. Direct use of the BS 8110 (23) strength grades may be irrelevant for Sri Lankan practice. It is probably this inability to carry out such surveys across Europe that has resulted in the draft European standards reverting back to specifying by mix proportions (24-26).

One of the major problems in making specifications for Sri Lankan practice will be to answer the question as to whether grade 20 concrete, which is the most widely used grade in Sri Lanka, is permissible or not. Most modern codes of practice (23,27) specify a minimum grade of 25 for durability purposes if strength is measured by cube or equivalent cube strength (See Table 4). However, recent specifications drawn up for Sri Lankan practice - i.e. the "Model Code" (32) and the ICTAD Specifications (33) - have continued the use of grade 20 concrete, probably basing their recommendations on the now outdated CP 114 (34) and CP 110 (12) respectively.

On the other hand, the use of grade 20 concrete cannot be rejected outright, because environmental conditions in Sri Lanka are probably less harsh than those in the U.K or Australia, for example. Furthermore, most concrete surfaces in Sri Lanka receive a mortar rendering, which provides additional protection. Finally, structures built out of grade 20 concrete have not performed too badly. Hence, it may be permissible to continue the use of grade 20 concrete, especially if it is shown that this does not violate the spirit of BS 8110 (23), which is the code used for the design of concrete structures in Sri Lanka.

Such an exercise is presented in a companion paper (35), based on a batching plant survey undertaken in Sri Lanka, which indicated that the grades corresponding to the maximum free water/cement ratios and minimum cement contents in Table 1 are around 10 N/mm^2 lower for typical Sri Lanka concretes than for U.K. concretes. Thus, it is in fact possible to reconcile the use of grade 20 concrete, for mild exposure situations, with the durability provisions of BS 8110 (23). The conditions under which such reductions from the BS 8110 (23) grades can be made are spelt out more fully in the companion paper (35).

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TABLE 1 (Extracted from BS 8110 : 1985)

Table 3.4 Nominal cover to all reinforcement (including links) to meet durability requirements (see note)

Conditions of exposure (see 3.3.4)	Nominal cover				
	mm	mm	mm	mm	mm
Mild	25	20	20*	20*	20*
Moderate	–	35	30	25	20
Severe	–	–	40	30	25
Very severe	–	–	50†	40†	30
Extreme	–	–	–	60†	50
Maximum free water/cement ratio	0.65	0.60	0.55	0.50	0.45
Minimum cement content (kg/m^3)	275	300	325	350	400
Lowest grade of concrete	C30	C35	C40	C45	C50

*These covers may be reduced to 15 mm provided that the nominal maximum size of aggregate does not exceed 15 mm.

†Where concrete is subject to freezing whilst wet, air-entrainment should be used (see 3.3.4.2).

NOTE 1. This table relates to normal-weight aggregate of 20 mm nominal maximum size.

NOTE 2. For concrete used in foundations to low rise construction, see 6.2.4.1).

TABLE 2 (Extracted from AS 3600 - 1988)

REQUIRED COVER WHERE STANDARD FORMWORK AND COMPACTION ARE USED

Exposure classification	Required cover, mm				
	Characteristic strength (f'_c)				
	20 MPa	25 MPa	32 MPa	40 MPa	50 MPa
A1	20	20	20	20	20
A2	(50)	30	25	20	20
B1	—	(60)	40	30	25
B2	—	—	(65)	45	35
C	—	—	—	(70)	50

NOTE: Bracketed figures are the appropriate covers when the concession given in Clause 4.3.2, relating to the strength grade permitted for a particular exposure classification, is applied.

TABLE 3 – CORRELATING STRENGTH WITH PERFORMANCE CRITERIA

(From Ref. 11)

(a) Minimum 28-day Strength Levels to Satisfy Limiting Values of Sorptivity (6.5 mm/h$^{0.5}$) and Carbonation (45 mm/y$^{0.5}$) for Concretes Exposed to 'Very Severe' Environment

Set	Concrete	Minimum values of F_{28} (MPa) to satisfy							
		Sorptivity				Carbonation			
		30	35	40	45	30	35	40	45
1	Plain	√				√			
2	WR	√				√			
3	WR	√				√			
4	FA			√		√			
5	FA (40%)				√			√	
6	F-W		√				√		
7	FA			√			√		
8	F-W		√				√		
9*	AE	√				√			
10*	F-W-A		√				√		
11	Plain	√				√			
12	AE	√				√			
13	W-A	√				√			
14	F-W-A	√					√		
15	Plain			√		√			
16	FA				√		√		

* Minimum strengths estimated from limited data.

(b) Minimum 28-day Strength Levels to Satisfy Limiting Values of Sorptivity (8 mm/h$^{0.5}$) and Carbonation (55 mm/y$^{0.5}$) for Concretes Exposed to 'Severe' Environment

Set	Concrete	Minimum values of F_{28} (MPa) to satisfy							
		Sorptivity				Carbonation			
		20	25	30	35	20	25	30	35
1	Plain		√				√		
2	WR		√				√		
3	WR		√				√		
4	FA				√			√	
5	FA (40%)				√				√
6	F-W		√				√		
7	FA				√			√	
8	F-W			√			√		
9*	AE		√				√		
10*	F-W-A			√			√		
11	Plain		√				√		
12	AE		√				√		
13	W-A		√				√		
14	F-W-A		√				√		
15	Plain			√			√		
16	FA				√			√	

* Minimum strengths estimated from limited data.

(c) Minimum 28-day Strength Levels to Satisfy Limiting Values of Sorptivity (9 mm/h$^{0.5}$) and Carbonation (60 mm/y$^{0.5}$) for Concretes Exposed to 'Moderate' Environment

Set	Concrete	Minimum values of F_{28} (MPa) to satisfy							
		Sorptivity				Carbonation			
		20	25	30	35	20	25	30	35
1	Plain		√			√			
2	WR		√			√			
3	WR		√			√			
4	FA			√			√		
5	FA (40%)			√				√	
6	F-W	√					√		
7	FA			√			√		
8	F-W		√				√		
9*	AE		√				√		
10*	F-W-A		√				√		
11	Plain		√				√		
12	AE		√				√		
13	W-A	√					√		
14	F-W-A	√					√		
15	Plain		√				√		
16	FA				√			√	

* Minimum strengths estimated from limited data.

(d) Minimum Requirements for Cover and 28-day Strength, for Various Exposure Conditions

Exposure		Cover (mm)	28-day strength (MPa)
Very severe:	B2	45	40
Severe:	B1	40	30
Moderate:	A2	30	25

(Note: Mixes with low early strength and fly ash mixes without water-reducing agents may require a larger cover or a higher 28-day strength.)

TABLE 4 - NOMINAL COVER (mm) TO ALL REINFORCEMENT AS PER U.K.& AUSTRALIAN DURABILITY REQUIREMENTS

Exposure Condition	Characteristic Cube Strength (N/mm²)						
	25	30	35	40	45	50	55
Mild		25	20	20	20	20	
	(20)	(20)	(20)		(20)		(20)
Moderate			35	30	25	20	
		(30)	(25)		(20)		(20)
Severe				40	30	25	
			(40)		(30)		(25)
Very Severe				50	40	30	
					(45)		(35)
Extreme					60	50	
							(50)

Note : Plain figures are taken directly from BS 8110 : 1985, while those in parentheses are derived from values in AS 3600 - 1988. The lower limit of 20 mm is governed by the nominal maximum aggregate size.

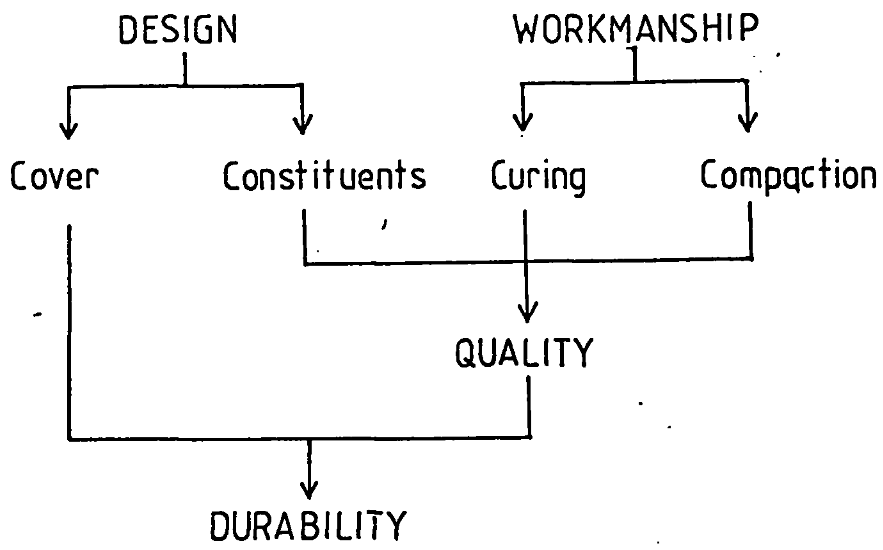


FIGURE 1 - FACTORS CONTRIBUTING TO DURABILITY

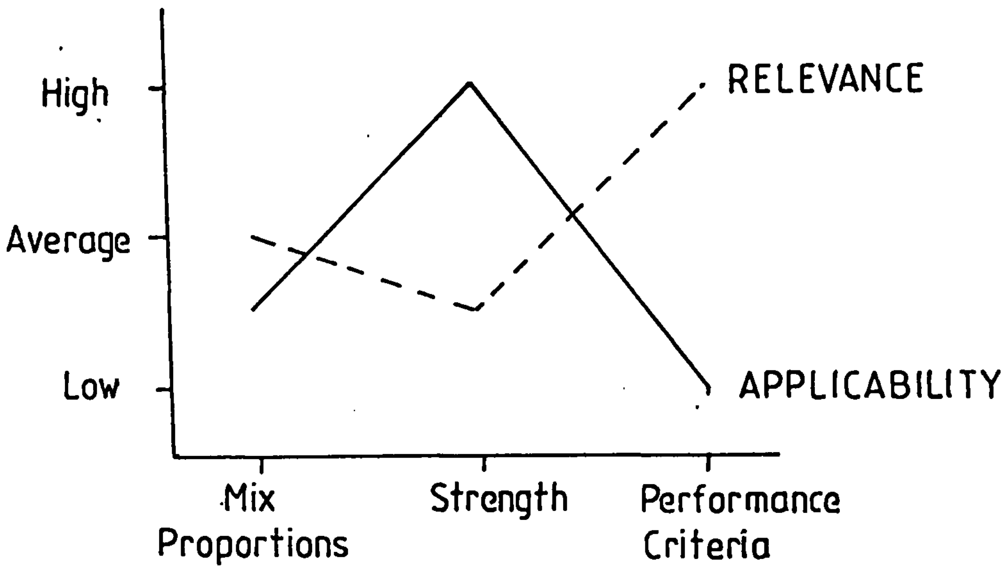


FIGURE 2 - ASSESSMENT OF METHODS OF SPECIFYING FOR DURABILITY

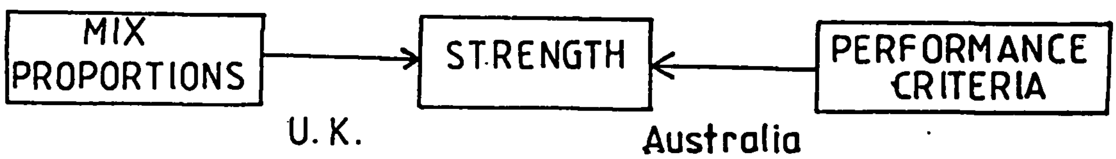


FIGURE 3 - IMPROVING THE RELEVANCE OF STRENGTH TESTING

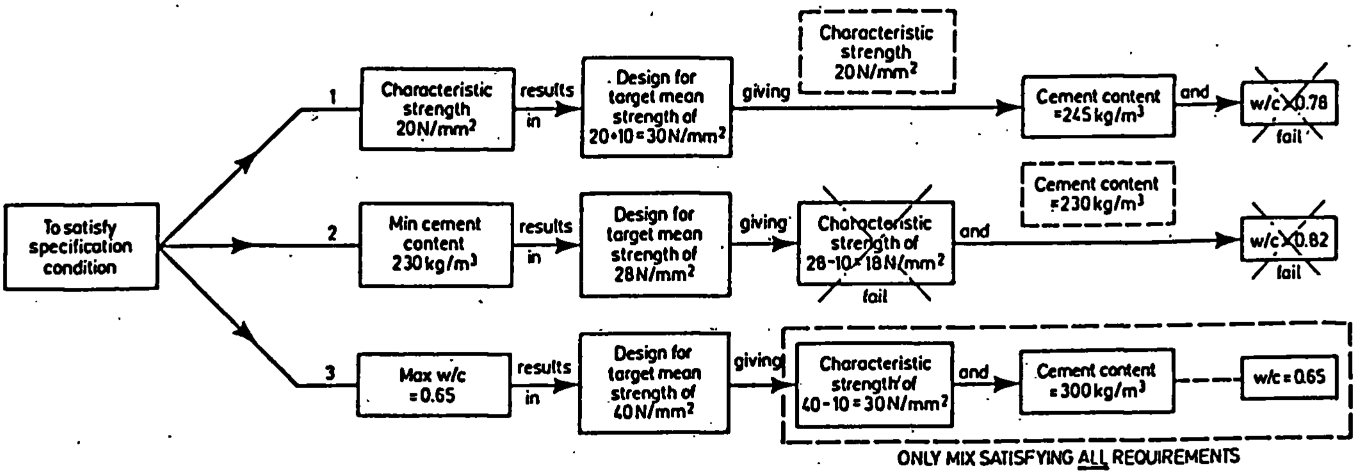


FIGURE 4 - CONFLICTING AND UNECONOMIC SPECIFICATIONS ARISING OUT OF CP 110 (From Ref. 10)

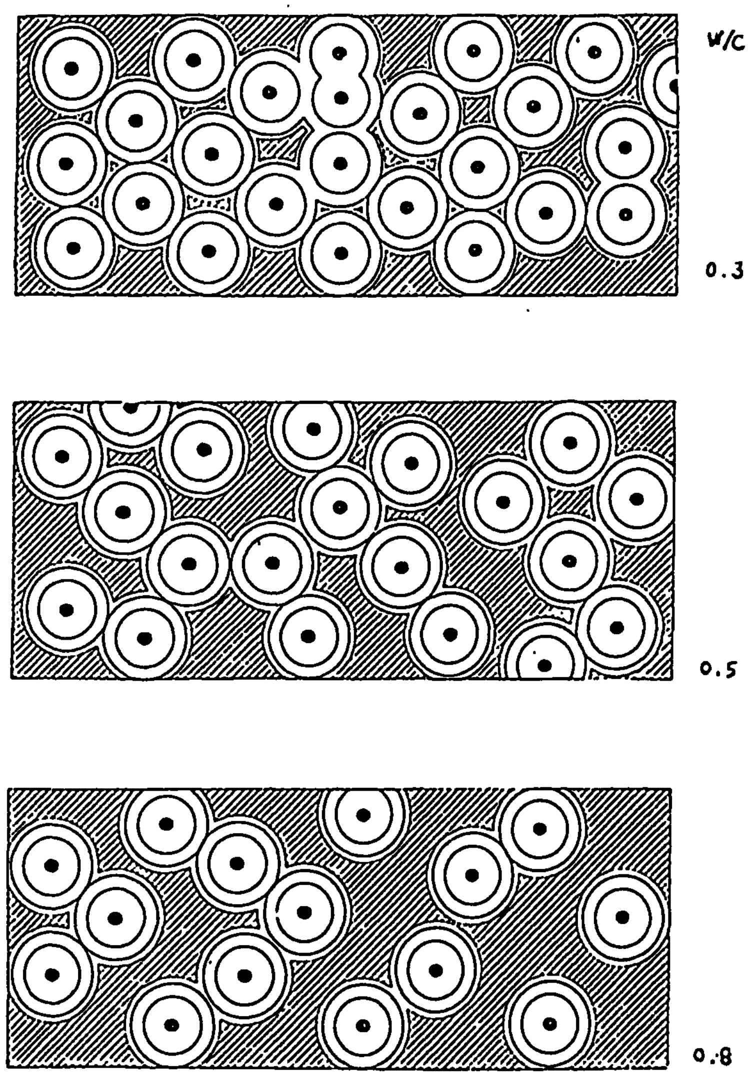
Typical effect of changes in OPC strength on w:c ratio

	Strength (N/mm^2) for w/c				
	0.4	0.5	0.6	0.7	0.8
1950	46	36	28	22	17
1960	52	45	35	27	21
1970	65	51	40	31	24
1980	72	56	44	35	27
1990?	77	60	47	38	30

Lines are contours of equal strength

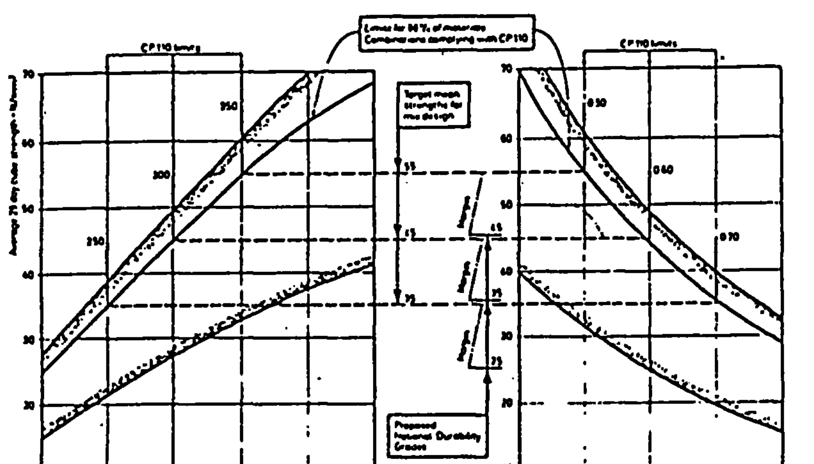
The central column (w/c - 0,6) is for the concrete used for BS 12 compliance.

FIGURE 5 - VARIATION OF OPC STRENGTH IN THE U.K. OVER 4 DECADES (From Ref.1)



The effect of initial cement particle spacing on the permeability of concrete

FIGURE 6 (Extracted from Ref. 1)



Relationship between strength, cement content, and water/cement ratio for materials throughout the UK.

FIGURE 7 (Extracted from Ref. 10)