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Specifying cement content for concrete durability: why less is more

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ABSTRACT: Specifications for concrete durability are often prescriptively based with minimum cement or binder contents being stipulated as part of the compliance requirements for concrete. The rationale for prescribing minimum cement contents appears to be based on concerns that Portland cement and other binders may be able to achieve sufficient strength for structural performance without having the requisite durability. Analysis of research investigating the influence of minimum cement contents found this approach to be conservative and may in fact negatively affect the potential durability of concrete structures. This paper presents a study on the influence of binder content, water/binder ratio, binder type and curing on strength of concrete and transport properties that affect durability. Reducing the paste content of concrete has the effect of lowering the porous phase of the material, which thereby limits absorption, permeation and diffusion characteristics of the material since aggregate phases are generally denser and more impermeable. Results from this study confirmed that concrete with lower binder contents had better quality microstructure for durability than similar concrete with the same water/binder ratios but greater cement contents. Prescriptive limits on cement contents take no account for concrete mix and material optimization and run counter to performance-based design principles. Recommendations from this study are that performance-based specifications are a more rational way of achieving durable concrete structures than prescriptive specifications. This study recommends specifying performance criteria provided these are known to influence the service performance of concrete structures.

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ABSTRACT

Specifications for concrete durability are often prescriptively based with minimum cement or binder contents being stipulated as part of the compliance requirements for concrete. The rationale for prescribing minimum cement contents appears to be based on concerns that Portland cement and other binders may be able to achieve sufficient strength for structural performance without having the requisite durability. Analysis of research investigating the influence of minimum cement contents found this approach to be conservative and may in fact negatively affect the potential durability of concrete structures. This paper presents a study on the influence of binder content, water/binder ratio, binder type and curing on strength of concrete and transport properties that affect durability. Reducing the paste content of concrete has the effect of lowering the porous phase of the material, which thereby limits absorption, permeation and diffusion characteristics of the material since aggregate phases are generally denser and more impermeable. Results from this study confirmed that concrete with lower binder contents had better quality microstructure for durability than similar concrete with the same water/binder ratios but greater cement contents. Prescriptive limits on cement contents take no account for concrete mix and material optimization and run counter to performance-based design principles. Recommendations from this study are that performance-based specifications are a more rational way of achieving durable concrete structures than prescriptive specifications. This study recommends specifying performance criteria provided these are known to influence the service performance of concrete structures.

1. BACKGROUND

Concrete specifications are written to ensure that the potential structural and durability performance of the material can be assured in service. Most structures require concrete that achieves a minimum compressive strength together with other hardened properties such as dimensional stability and durability. Many authors recommend a performance-based approach for concrete specifications since this provides more flexibility to concrete suppliers and contractors (Wassermann et al 2009, Alexander et al 2008). What is less clear is what measure of performance is most relevant to concrete structures.

Prescriptive specifications, which still represent the majority of specifications in force, often stipulate minimum cementitious contents or have water/cement ratio limits. While such an approach appears to have a direct relationship with compressive strength, these material limits may have little correlation with properties such as dimensional stability and transport properties that affect durability of concrete (Harrison et al 2012). In this context, the term "transport properties" refers to the concrete's ability to resist the ingress of deleterious substances and encompasses properties such as permeability, conductivity, and sorptivity. In some cases, the use of higher cement contents or lower water/cement ratios has been shown to increase the drying shrinkage of concrete (Alexander 1998). Further, high cement contents increase the risk of thermal cracking in mixes with low w/b ratio and may increase the risk of Alkali Silica Reaction.

Historically concrete was produced with little or no chemical admixtures and cement content was found to directly influence both strength and microstructural properties that affected durability. With the advent of modern admixtures in concrete technology, there has been a steady decoupling of cement or binder content from concrete quality. The quality of modern concrete in terms of structural and durability performance is now mostly related to water/binder ratio and binder type rather than merely the amount of binder used in concrete.

Several systematic studies have been undertaken over the last twenty years investigating the effect of varying cement content at constant water/cement ratio on concrete properties such as strength and transport mechanisms that influence durability (Mackechnie, 2002, Buenfeld and Okundi, 2004, Dhir et al., 2004, Kolias and Georgiou, 2005, Yigiter et al., 2007, Wassermann et al., 2009, Grdic et al., 2010, Harrison et al. 2012). Findings from these studies generally showed an improvement in concrete quality when cement content was decreased while keeping water/cement ratio constant. This can be ascribed to the reduction in paste volume such that the concrete matrix had increasing amounts of relatively impermeable aggregate phases and less paste with higher porosity. In many cases, the improvement in microstructural properties was more than would be predicted from the change in the relatively impermeable aggregate phase for more permeable paste phases. This extra benefit may be partly due to varying amounts of chemical admixtures used in the different mixes and differing consistence levels that would affect plastic properties such as bleed and settlement.

This research investigated the relationship, for a range of common South African binder combinations, between cement content and Durability Index values, which help to characterise the potential durability of concrete.

2. EXPERIMENTAL METHODOLOGY

Binders used in this study included Portland cement CEM I 52.5 N (denoted PC), fly ash (FA) and ground granulated blast-furnace slag (GGBS). The chemical analyses of these binders are shown in Table 1. Aggregates used to produce these laboratory concrete mixes were crushed greywacke 19 mm stone and a 50/50 blend of unwashed greywacke crusher sand and a siliceous dune sand. Physical properties of these aggregates are shown in Table 2.

Table 1: Oxide proportions of cementitious binders (%)

Oxide	PC	FA	SL
SiO_2	21.1	54.1	34.2
Al_2O_3	4.0	32.9	16.5
Fe_2O_3	3.4	3.3	0.4
CaO	65.8	4.7	32.8
MgO	0.9	1.3	10.4
SO_3	2.3	0.4	1.4
Na_2O	0.7	0.6	0.9
K_2O	0.1	0.6	0.0

Table 2: Physical properties of fine and coarse aggregates

Physical Property	Coarse aggregate	Crusher sand	Dune sand
Nominal size (mm)	19	5	2
Specific gravity	2.68	2.60	2.63
Fineness modulus	-	3.11	1.92
Loose bulk density (kg/m³)	1440	1500	1600
Voids ratio	0.463	0.423	0.392
Particle shape	Angular	Sub-angular	Rounded

The concrete mix designs (paste content) are shown in Table 3. For each water/binder ratio, four different water contents were chosen to produce a practical range of binder contents. In total, 36 different concrete mixes were produced. Chemical admixtures including a mid-range and high-range water reducing admixture were used to produce concrete with sufficient workability to allow adequate compaction. Concrete was mixed in a high shear pan mixer in the laboratory with consistence levels being between 40 mm and 200 mm. Binder contents varied from 258-488 kg/m³ while paste contents varied from 237-367 l/m³ (i.e. 24.0 – 37% by volume).

Concrete for compressive strength testing was cured according to SANS in water at 230C until either 28 or 90 days. Concrete for penetrability testing (Durability Indexes) were exposed to two different curing regimes. The first was moist curing, which involved the placing of the specimens in water at approximately 20°C one day after casting, immediately after stripping (with 20°C being the average temperature under ambient laboratory conditions). The second was laboratory air curing, where the specimens were stripped the day after casting, placed in the same moist conditions as described above for 3 days, then removed from the curing tanks and exposed to controlled conditions of approximately 20°C and 50% relative humidity in the lab. The 3-day moist curing period was selected to closely resemble curing practices commonly adopted in typical site conditions.

Testing for compressive strength was done in accordance with SANS 5863:2006 while transport properties (Durability Indexes) were measured according to SANS 3001 - CO3-2 (Oxygen Permeability) and SANS 3001 - CO3-3 (Chloride Conductivity). Water sorptivity was tested according to the UCT Durability Index Manual (2010). Samples for Durability Index testing were wet-cured for the anticipated curing duration (i.e. 3 or 28 days) and prepared for testing at an age of 28 days.

3. RESULTS AND DISCUSSION

Concrete was cured in water until testing at either 28 or 90 days for compressive strength and the durability-related properties of absorption, permeation and diffusion. Since binder content was the key parameter being investigated, results are compared on that basis in the sections below.

3.1 Compressive strength

The 28-day compressive strength of concrete was generally found to decrease with increasing binder content although differences were relatively low and averaged less than 5 MPa for binder reductions of 65 to 100 kg/m³. This is shown in Figure 1.

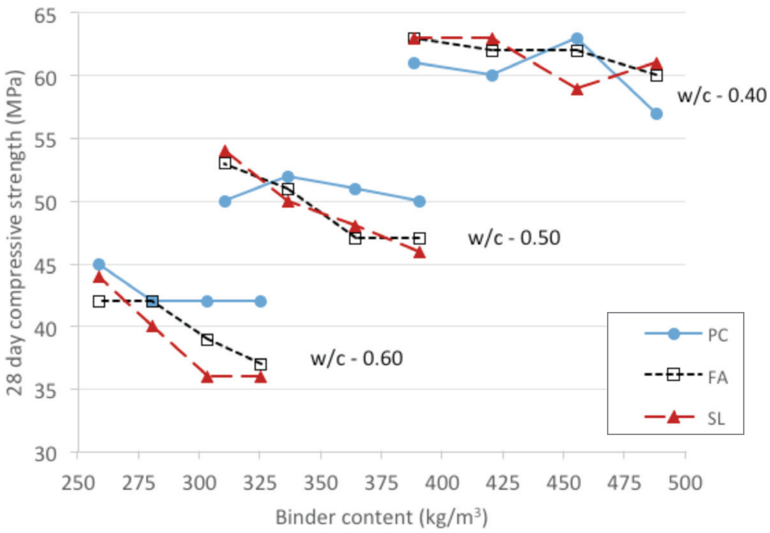

Figure 1: Binder content versus compressive strength after 28 days

Table 3: Concrete mix designs (per cubic metre of concrete)

w/b ratio	Water (l/m³)	PC (kg/m³)	SCM# (kg/m³)	Paste (l/m³)	PC (kg/m³)	FA (kg/m³)	Paste (l/m³)	PC (kg/m³)	SL (kg/m³)	Paste (l/m³)
0.40	195	488	0	350	341	146	367	244	244	357
	182	455	0	327	319	137	343	228	228	333
	168	420	0	302	294	126	316	210	210	307
	155	388	0	279	271	116	292	194	194	284
0.50	195	390	0	319	273	117	333	195	195	324
	182	364	0	298	255	109	311	182	182	303
	168	336	0	275	235	101	287	168	168	279
	155	310	0	254	217	93	265	155	155	258
0.60	195	325	0	299	228	98	310	163	163	303
	182	303	0	278	212	91	289	152	152	283
	168	280	0	257	196	84	267	140	140	261
	155	258	0	237	181	78	247	129	129	241

 # Supplementary cementitious material

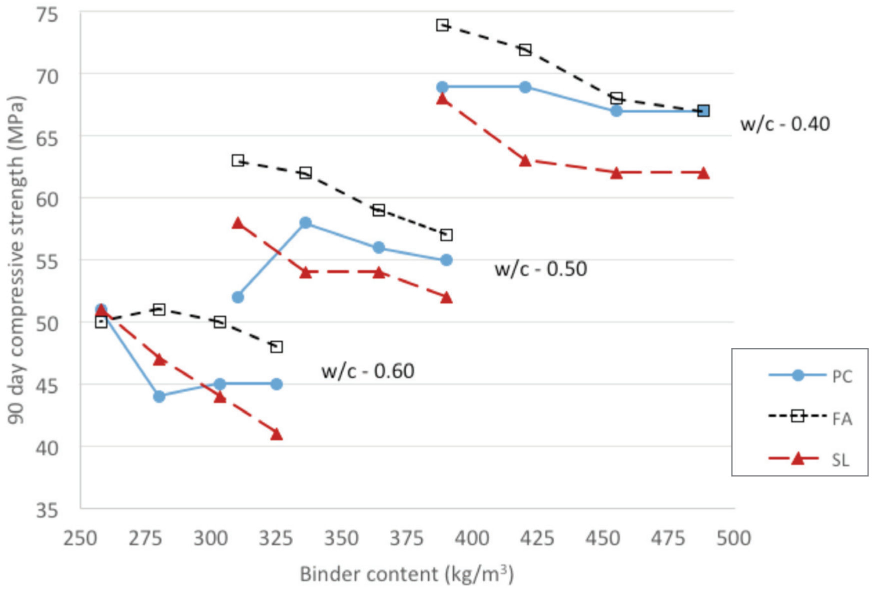

Figure 2: Binder content versus compressive strength after 90 days

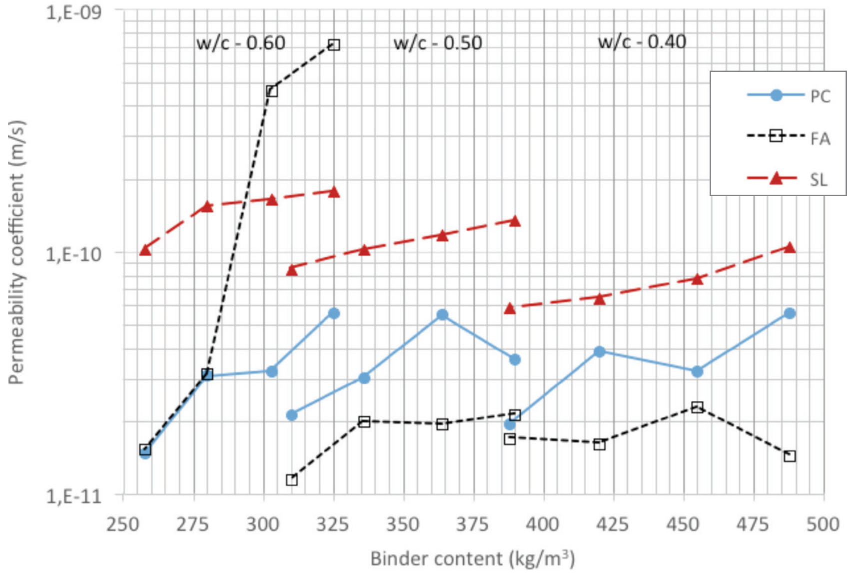

Figure 3: Permeability coefficient versus binder content – 28 days wet curing

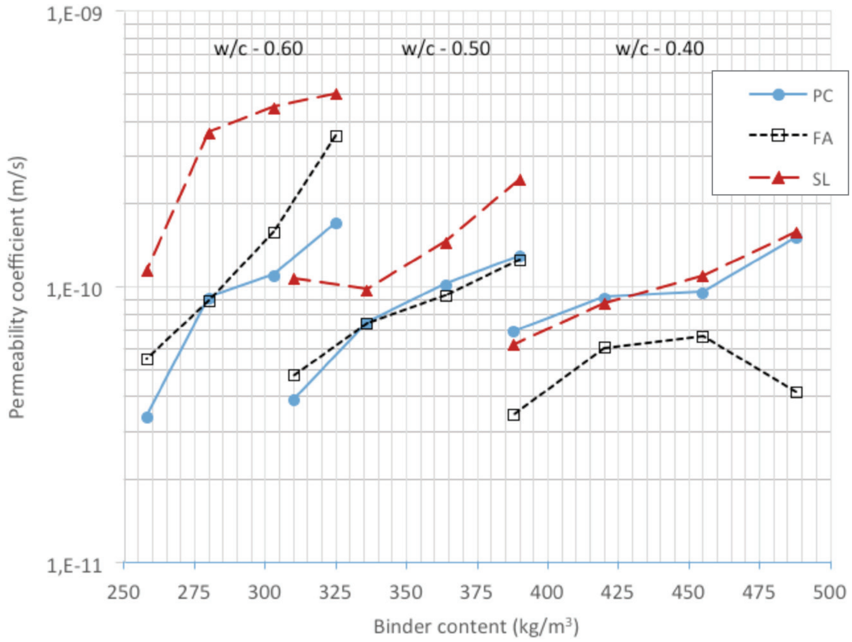

Figure 4: Permeability coefficient versus binder content – 3 days wet curing

Several possible reasons may be postulated for these differences. The most likely explanation would be that easier crack propagation is possible through concrete containing more paste. This would result in better strength provided paste content was not reduced too much that it significantly affected the workability of concrete. Grdic et al (2010) found that the optimum aggregate/cement ratio for strength was between 5-6 for concrete with water/binder ratio of approximately 0.50, which is a binder content of around 300-320 kg/m³.

Compressive strength measured after 90 days of wet curing showed similar trends to that observed after 28 days, except that fly ash concrete generally had higher strength compared with PC concrete (Figure 2). This is due to continued cementing reactions that occur from the pozzolanic reaction in fly ash concrete and the slower reaction rate in slag concrete.

3.2 Oxygen permeability

The OPI is commonly used to characterise a concrete's resistance against carbonation, a higher index value indicating higher potential durability. Results from oxygen permeability testing were analysed by comparing the coefficient of oxygen permeability of concrete specimens prepared in the standard fashion (50°C oven drying for 7 days). Figures 3 and 4 show these results. Permeability was found to increase fairly consistently with increasing binder content with the exception of higher strength fly ash concrete. Slag concrete was found to have higher permeability regardless of water/binder ratio and curing compared with PC or FA concrete. At low water/binder ratios, the influence of binder content was less obvious than at higher water/binder ratios.

3.3 Water sorptivity

The Water Sorptivity Index is used as an indication of the concrete's tendency to absorb water, which is an important property related to both chloride ingress and carbonation. A lower sorptivity value relates to higher durability. Absorption of concrete was found to decrease with lower water/binder ratios but tended to increase as binder contents increased for mixes of the same w/b ratio. This can be seen in Figures 5 and 6, where sorptivity values are compared against binder content. With the exception of a few outliers, the relationship between sorptivity and binder content was found to be quite consistent at all water/binder ratios and binder types.

3.4 Chloride conductivity

The Chloride Conductivity Index relates to the rate of chloride ingress into concrete, a lower index value indicating better durability. The chloride conductivity results are shown in Figures 7 and

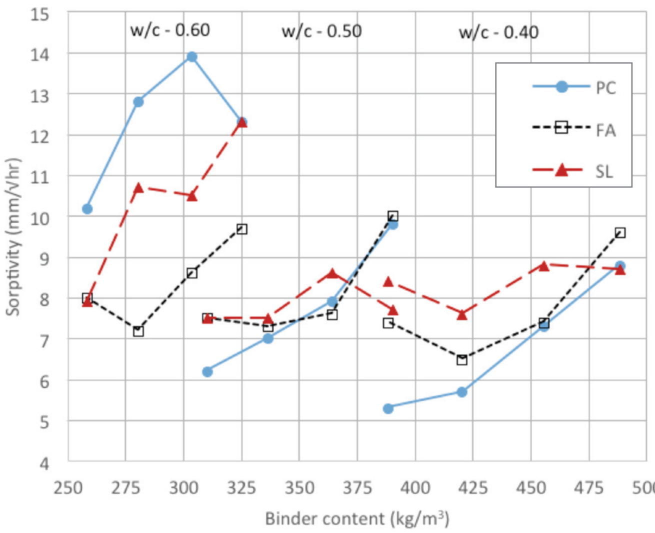

Figure 5: Sorptivity versus binder content – 28 days wet curing

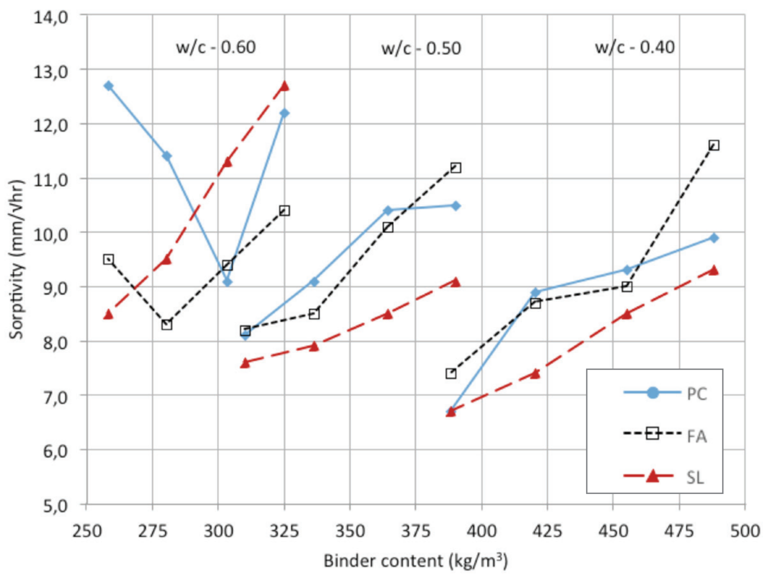

Figure 6: Sorptivity versus binder content – 3 days wet curing

8. Trends observed for the three different binder types are as follows:

- PC concrete had highest chloride conductivity values and was significantly affected by w/b ratio and binder contents
- FA concrete had intermediate values and was more influenced by binder content at higher w/b ratios, and was strongly influenced by lack of wet curing
- SL concrete generally had lowest chloride conductivity values and showed only a slight influence of binder content for constant w/b ratio.

3.5 Overall comparison

The influence of binder content on the hardened properties of concrete is compared in Table 4 where measured properties are given as percentages of that same property for the concrete with lowest paste content (i.e. concrete with water content of 155L/m³). Looking at these comparisons the following patterns can be clearly seen:

- Compressive strength decreases slightly with an increased paste content in concrete
- Porosity increases as would be expected when the paste content increases
- Oxygen permeability increases quite significantly for higher paste contents
- Water sorptivity generally increases as the paste content increases
- Chloride conductivity increases steadily in concrete with higher paste contents

Interestingly, Table 4 shows that the durability index properties are much more affected than concrete strength, generally suffering far greater relative increases and thus reduced potential durability. This reinforces the point often made that durability is more detrimentally affected in

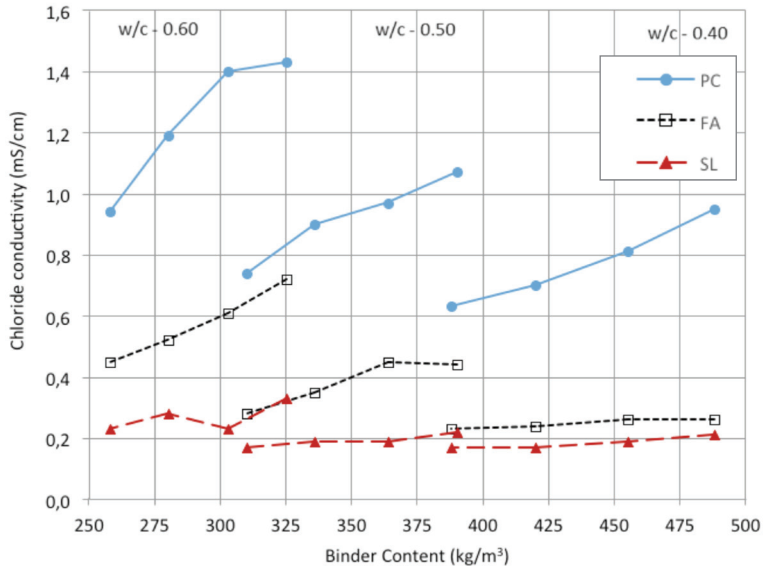

Figure 7: Chloride conductivity versus binder content – 28 days wet curing

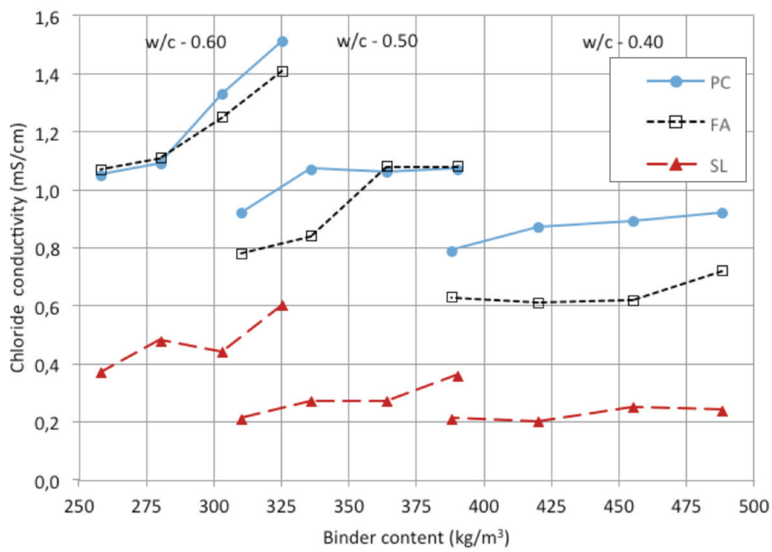

Figure 8: Chloride conductivity versus binder content – 3 days wet curing

concrete mixes with high water and cement contents. Further, the trends outlined in Table 4 are likely to be exaggerated in concretes cured for limited periods such as only 3 days wet curing.

The apparent detrimental effect of increased binder content on potential durability is also more pronounced in concrete at higher water/binder ratios (0.60). This is because in concrete with lower water/binder ratios, there is a refining effect produced by unhydrated binder particles on the microstructure. This limits the effects of bleeding and settlement thereby causing an overall densification of the concrete matrix. However, as the water/binder ratio increases, the proportion of paste generally also increases and the higher paste volume results in a larger fraction of voids and interconnected pore structure. The extra expense of adding more binder to concrete therefore does not automatically result in better quality concrete in terms of strength and durability.

Table 4: Summary of relative 28 day properties based on lowest water (and binder) content for wet cured concrete (%)

Property	Binder	Water - 155 L	Water - 168 L	Water - 182 L	Water - 195 L
Strength	PC	100.0	98.7	100.0	95.6
	FA	100.0	98.0	93.6	91.1
	SL	100.0	94.7	88.8	88.8
Porosity	PC	100.0	103.6	110.1	113.4
	FA	100.0	103.0	114.6	117.2
	SL	100.0	102.5	111.3	118.8
Oxygen Permeability	PC	100.0	179.2	214.7	266.1
	FA	100.0	150.4	240.3	468.7
	SL	100.0	204.6	247.8	286.2
Water Sorptivity	PC	100.0	117.6	132.8	143.4
	FA	100.0	91.7	103.1	128.0
	SL	100.0	108.4	117.3	120.6
Chloride Conductivity	PC	100.0	120.8	137.7	149.4
	FA	100.0	115.6	137.5	147.9
	SL	100.0	112.3	107.0	133.3

CONCLUSIONS

Specifications for the supply of concrete for structural purposes need to address the durability of the material. Using prescriptive-based specifications that set limits on the binder content in concrete has previously been shown to be too conservative and may not in fact improve the durability performance of a concrete structure. Research findings from this study further corroborate that view and suggest that performance-based approaches should rather be used in specifications. Experimental findings suggest that while compressive strength and potential durability are interlinked, the relationship between mix design and durability is not consistent. An increase in water/binder ratio produced lower durability index properties for all binder types and both curing regimes, as expected.

Increasing the binder content at a constant water/binder ratio increased the paste volume, which had the effect of reducing the potential durability as measured by transport properties (durability indexes). These reductions differed in extent for each durability index investigated and were influenced by water/binder ratio, binder type and curing regime. Increases in paste volume caused more significant reductions in durability potential at higher water/binder ratios of 0.60. At low water/binder ratios of 0.40, the effects of differing binders contents were less pronounced and results generally indicated very good potential durability.

Findings presented in this paper show that any beneficial effects associated with an increase in binder content are limited and highlight the need for a more useful performance-based specification approach. Durability specifications can be much more effective if the primary deterioration mechanism is understood and appropriate performance limits are specified to ensure compliance rather than applying a minimum cement content that might not be appropriate. ▲

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