



Low Heat and Eco-friendly Fly Ash Concretes

**A Project
by Unibeton Ready Mix for EcoSmart Foundation**

Final Report

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1. INTRODUCTION

ECOSMART foundation and UNIBETON READY MIX, a member of AL FARA'A GROUP of UAE have cooperated to research the initial potential for use of Fly Ash in ecology-friendly, low CO₂ commercial concretes in the UAE.

This report summarizes research findings carried out to-date.

2. DESIGN BACKGROUND AND CRITERIA

2.1 Concrete specifications in UAE

Local UAE specifications have a high durability emphasis so mixes are often over-designed from the point of view of strength in order to meet a plethora of durability criteria, e.g. Rapid Chloride Permeability, and surface absorption etc.

Specification compliance and enforcement generally involves a third party and (separate) third party testing.

Specification interpretation tends to be conservative, relying upon pass-fail principles rather than the compliance rules in the specification.

2.2 Concrete grade and type

Typical UAE concretes tend to be high strength, low water-cementitious ratio pumpable concretes, for example, the weighted average grade of concrete delivered by UNIBETON in 2006 was about 44MPa. All designs are usually designed at the outset to be pumpable.

The on-site pumpable slump which is commonly specified is 125mm. This requires that the slump at the supply plant is in excess of 150mm for a typical delivery time of less than 45 minutes.

Regarding concrete type, concrete with cement, cement-GGBS or cement-GGBS-micro silica is widely practiced, to follow up with specification requirement, which varies with different projects.

2.3 Raw materials

Raw materials for concrete products include 1) cementitious materials such as OPC, GGBS, Micro silica, and fly ash, 2) aggregate and sand, and 3) admixtures, etc.

2.3.1 Cementitious materials

2.3.1.1 Cement

Portland and sulphate resisting cement are manufactured and/or ground locally in UAE.

UNIBETON does not test cement independently so mill certificates are relied upon for indications of performance characteristics which are usually reported to BS standard.

Cement strength appears to vary by about 5MPa at the medium strength level (40MPa).

There is currently some concern over cement testing which is perhaps related to test precision however as cement is ground from imported clinker as well as manufactured using local materials, it is possible that clinker quality is variable as well.

Portland cement ex. Fujairah Cement Industries was used in the fly ash trials referred to in this report.

2.3.1.2 GGBS (ground, granulated, blast furnace slag)

Slag is available in the UAE and is commonly specified on basis of durability and low heat requirements. Therefore, the trial process should include GGBS and GGBS/Microsilica mixes as “Control concretes” in order to realistically appraise equivalent fly ash designs under UAE commercial/technical conditions.

Blast Furnace slag ex. Sharjah Cement was used in the fly ash trials referred to in this report.

2.3.1.3 Fly ash

Fly ash is used in the UAE and the main supply source appears to be India.

Information apart from data sheets for marketing purposes is not freely available on performance in local (UAE) concretes, however most suppliers claim compliance with BS 3982 or ASTM 618.

The Fly ash supply chain is relatively undeveloped in UAE and some suppliers appear to be traders only, relying upon support information and tests from local Indian sources.

Fly ash used in ECOSMART project is POZZO 63 from DIRK of India, which is an established supplier having fly ash classification and in-house QA/QC procedures.

2.3.1.4 Microsilica

Microsilica is commonly specified and available from international and local (gulf) suppliers. ELKEM Microsilica was used in the ECOSMART trials.

2.3.2 Aggregates and sand

Adequate quality of limestone aggregates in 20mm, 10mm and <5mm crushed sand sizes are available.

Natural (dune) sand is also used for economy, to overcome deficiencies in mix grading uniformity caused by segregation of crushed sand on stockpiles, and improve fresh concrete appearance and finish.

There is some prejudice against the use of dune sand with limits set at not more than 300kg/m³ in some specifications.

The shape of the limestone aggregate is good with slight elongation and flakiness, increasing with decreasing particle size whilst the dune sand is single-size and rounded containing a high amount of material below 300 microns in size.

Both materials compliment each other in achieving efficient mix designs. Both types of aggregates tend to be dry when batched although there is occasional surface moisture which is compensated for. There are times when either or both materials are below saturated, surface-dry condition in use.

Absorption values are very low at 0.8 and 0.85% respectively for Limestone and Dune sand and these are compensated for in batching.

For supply source, limestone aggregates ex. Ras Al Khaima was used in the fly ash trials referred to in this report. Dune Sand ex. Al Ain was used in the fly ash trials referred to in this report.

2.3.3 Water

Potable water is used and concrete mixes are subject to temperature control using chilled water and crushed ice in the hot months.

Water is relatively expensive and typical pumpable designs using type G admixtures contain between 150-170 litres of water at pumpable workability.

2.3.4 Admixtures

UNIBETON uses a Type G Napthalene-based superplasticizer from either FOSROC or He-Be chemicals to treat almost all concrete whilst other UAE suppliers tend to use a combination of lignin and Napthalene products to achieve different outcomes at minimum cost. Polycarboxylates are also commonly used in high performance concretes.

Admixture dosage is typically very high indeed (often exceeding 1.5% BWC) in order to achieve very low water-cement ratios even in low grade mixes.

CONPLAST 495 (Naphthalene-based) ex. FOSROC was used initially in the phase 1 fly ash trials and other types and combinations subsequently used in phase 2 trials for specific performance.

2.4 Mix design

The research program on fly ash concrete includes two phases: Phase 1 and Phase 2.

The phase I mix design is based on the outcomes from a previous project on optimization of dune sand and pumpable concrete.

2.4.1 Design basis for Phase I mix design

Phase 1 trials was designed to use standard admixture in-use to initially test mixes using fly ash, against control concretes using either Portland cement, Cement-GGBS or Cement-GGBS-microsilica as these concretes are already established for most performance and durability specifications found in the market.

Prior to commencement of the ECOSMART project, commercial mix designs for the Abu Dhabi market were optimised during March-April 2007. The goal of these trials was to introduce more dune sand into the total fine aggregate whilst raising the combined coarse aggregate of pump mixes above 1000kg/m³.

Six key mixes representing low, medium, and high strength concretes were trialled using procedures to optimize fines (RMC technical procedure number 1).

Data was interpreted via regression to establish proportions for a range of pumpable concretes covering the approximate cement content range 150-500kg/m³.

The trials succeeded in maintaining a pumpable appearance in the concrete whilst raising the coarse aggregate to an average of 1100kg/m³.

By combining dune sand to achieve a variable grading in the fine aggregate it was also possible to raise the coarseness of the fine aggregate fraction gradually in parallel with the increasing cement content.

The outcome of these trials is contained in **Table 1** and **Chart 1** in **Appendix 1** (pumpable trial series March 2007).

2.4.2 Phase-I trials

Above mixes which tested in compression similarly to established designs, offered for the ECOSMART project a number of low, medium and high cementitious benchmark designs from which ECOSMART and control concretes could be tested for comparison, after modification to primary and supplementary cementitious proportions, actual water demand and yield, compared to Portland concretes.

Five designs ranging from 200-500kg/m³ were chosen for comparison purposes covering 95% of the range of cement content used locally.

Benchmark mix designs are listed in **Table 2**, and Final mix proportions used in these trials (adjusted for water demand and yield) are given in **Table 3**, in **Appendix 2**.

2.4.3 Phase-II trials

The Phase 2 trials took place immediately after fresh properties and 28 day results were reviewed from phase 1 providing direction to the choice of materials and mix design.

The requirements

The purpose of phase 2 trialling was to produce a commercial range of high strength designs for general piling and high rise pumping at LANDMARK project where client requirements are 80MPa and pumping height reaches 360 metres, or 72 storeys.

A set of internal targets for fresh and hardened properties at LANDMARK was set in order to measure performance of phase 2 mix designs, as follows;

- Concrete designs shall meet all specification requirements including strict durability parameters
- Mass concrete temperature requirements (peak<70°, differential <20°) require a low heat concrete with high fly ash as 80MPa column dimensions are self-insulating.
- Slump of >200mm, with retention of >80%, in 1 hr. preferably using stock admixtures rather than Polycarboxylates.
- 1 day strength of 12MPa to permit early stripping of falsework.
- Compression strength from laboratory trials to exceed characteristic strength by 3 x Standard deviations, or at least +15MPa.
- Fly Ash level to be 25-40% based on outcomes from phase 1 trials

The Phase 2 trials

The Phase 2 trials began with several mix designs generated from the same mix design curves used in phase 1 testing.

Proportions of cementitious material and aggregates were maintained however water demand was lowered compared to Phase 1 using a different admixture system.

Admixture methodology

Using a proven method for improvement of slump retention, ASTM Type D Lignin-based admixture was added at a dosage of 500mls per 100kg, followed in timed sequence after 45 seconds of mixing, by addition of Type F Naphthalene-based admixture, at a dosage of 2000 mls per 100kg, followed by a further 3 minutes of mixing.

It should be noted that the laboratory mixer used was a free-fall drum type, and admixture dosage was therefore elevated to manage the inefficiencies compared to forced-action mixing.

It was assumed that admixture economies would be realized using forced action mixing, and this was confirmed subsequently to be the case during initial plant evaluations.

Phase 2 Mix design

Three series of mixes containing 25, 32.5 and 40% Fly Ash were tested at cementitious levels of 440, 460, 480, and 500kg of total cementitious material per cubic metre and fresh and hardened properties were determined.

2.5 Testing program

Various fresh and hardened properties of several concrete groups were then measured over 90 days within the phase 1 trials to arrive at a basis for further modification and optimization of the Fly Ash group for a number of applications where fly ash is either specified, or preferred.

A list of the tests conducted during phase 1 comprising 30 separate concrete trials is listed in **Table 4, in Appendix 3.**

After initial training of French engineering students at the Umm Al Nar batch plant, all tests listed above were carried out in UNIBETON Mussafah laboratory, Abu Dhabi or Jebel Ali laboratory in Dubai during May - August 2007.

3. RESULTS AND DISCUSSION

3.1 Results from Phase 1 trials

3.1.1 Water demand

It can be observed in **Table 3 (Appendix 2)** that water demand for Portland, GGBS and GGBS/Microsilica* control concretes are nominally the same at about 17% of concrete volume.

*Note that in GGBS/Microsilica mixes microsilica is commonly used as a pore-blocking agent at 10kg/m³, in UAE concretes as well as for compression strength at (say) 6% BWC.

The influence of fly ash addition on water demand of related concrete was investigated. The effect of 25% Fly Ash on water demand is modest. Fly Ash concretes at 40 and 55% BWC appear to require a lower water demand at all cementitious levels arriving at a typical water requirement of 16% and 15% of concrete volume respectively compared to 17% in the Control group.

Consequently the effect of fly ash on WC ratio is very positive at 40 and 55% replacement although marginal at 25%.

3.1.2 Slump and slump retention

All slump test results are actually the mean values of two slump tests carried out on side-by-side basis to improve precision and eliminate the occasional odd value.

Water demand was always recorded immediately after recording a correct mean-of-two slump value.

The target initial slump of 150mm±20mm was achieved in all cases (control and fly ash group) however in the 55% fly ash group the slump was not stable and readily deformed after removal of the cone in a way similar to that observed in self-compacting concretes.

This meant that a team judgement had to be relied upon, augmented by further interval testing for slump retention in this group.

Slump retention is a very important fresh concrete parameter because of local conditions.

Each mix from the control and fly ash group was tested for slump at four 15 minute intervals after measurement of the initial value and all values were mean-of-two tests.

The curves generated for each mix and group were studied in order to understand the shape of curve generated compared to the Portland group and general expectations in regard to retention properties.

As it is assumed that fly ash concretes are required to be supplied in transit mixers the ideal curve is convex or at least linear over time as opposed to (say) a precast curve for which concave may be more suitable.

Plotted values were converted to percent retention values based on the initial value (100%) vs. time at 5 minute intercepts on the retention curve.

In phase 1 trials Control concretes appear to be generally superior in terms of slump retention compared to fly ash groups which is unexpected. (See **Appendix 4, Chart 2, and Appendix 5 Table 5**).

Upon examination of the curves for all groups at varying total cementitious content (200, 275, 350, 425 and 500kg/m³), fly ash concretes are reasonably competitive on retention at low cement content, but do not appear to have a consistent advantage compared to Portland concretes above 350kg/m³. (**Charts 2-1 to 2-5**)

The unexpected performance may be due to aggregate absorption, paste volume effects, choice of admixture, fly ash chemistry, humidity variation at the time of test etc.

3.1.3 Plastic density

The typical plastic density of the fly ash group of mixes is slightly lower than that of other combinations in the control group.

Lower water content is generally offset by higher mineral content as can be observed in the average AC ratios (**see Table 3, Appendix 2**).

3.1.4 Setting time

Charts 9 and 10 of Appendix 6 compare concrete mortar setting characteristics of the various binder combinations using Proctor needle methodology.

GGBS/MS and 25% Fly Ash blends show only a moderate extension of both initial and final set (slightly less than 1 hour and slightly more than 1 hour respectively) compared to Portland concretes. (See **Chart 9 of Appendix 6**)

The initial and final setting time of GGBS, 40 and 55% Fly Ash groups is however extended by 2-4 hours and 3-7 hours respectively compared to Portland concretes. (See **Chart 9 of Appendix 6**)

Raw data indicates GGBS and 25% Fly Ash groups are characterised by a very low scatter in setting times. whilst GGBS/MS, 40% and 55% Fly Ash groups conversely have very high scatter and therefore lower predictability compared to Portland, GGBS and 25% Fly Ash groups.

When Fly Ash groups are examined against only Portland groups, predictable extensions of both initial and final setting can be observed. (**Chart 10 of Appendix 6**)

3.1.5 Heat of Hydration

To invest positive input from fly ash to low heat concrete development, the heat of hydration test were conducted for samples of all the concretes in phase 1. The samples were placed in insulating containers and hydration monitoring commenced for about 60 hours using thermocouples, data logger and computer software.

The temperature of the fresh concrete was always within $25^{\circ}\pm 1^{\circ}\text{C}$ at the time of placing into the containers, and monitoring commenced for 60 hours from placement.

Based on the results obtained some heat appears to have been lost from the apparatus, however as the quality of insulation and standard of assembly was uniform throughout the tests, it has been assumed that all concretes were treated equally.

The temperature rise of various binder combinations per 100kg of binder is compared in **Table 6 of Appendix 7**.

The table indicates that 25, 40 and 55% Fly Ash blends compare very favourably to Portland cement, whilst 40 and 55% Fly Ash blends can be closely compared to GGBS and GGBS/MS concretes which are at higher levels of Portland cement replacement (65%).

Curves for heat-of-hydration of double and triple blended GGBS and Fly Ash concrete groups compared to the Portland concrete can be observed in **Charts 11-16 of Appendix 8**.

The 25% and 40% Fly Ash groups extend the period to reach peak temperature compared to Portland concretes by about 5 hours.

The GGBS and 55% fly Ash groups extend the period to reach peak temperature at least 15 hours compared to Portland concretes.

The latter groups could be considered as both low heat and “slow heat” concretes compared to Portland and 25 and 40% Fly Ash groups.

3.1.6 Bleeding, finishability and pumpability

As testing program **Table 4** of this report indicates, each concrete group was not tested in a quantitative or qualitative test but evaluated by visual assessment based on experience.

As the Portland designs used in these trials were originally intended for pumpable applications the effect of GGBS, GGBS/MS and Microsilica as secondary cementitious materials was an increase the binder volume in the various mixes, though this was sometimes offset by a decrease in water demand.

In any case the conclusion in regard to apparent finishability/pumpability was that all mixes visually appeared to be nominally the same as the original designs.

Bleeding was observed in all mixes containing 200kg of binder however this was not considered to be excessive.

3.1.7 Plastic shrinkage/Plastic settlement

Concretes which set slowly will tend to have greater “open time” or capacity to bleed compared to concretes which set more quickly, unless proportioning and/or use of alternative materials reduces the bleed rate.

Tests to compare Fly Ash and GGBS concretes for plastic shrinkage and plastic settlement were considered important in the 1st phase of testing.

Unfortunately workshop constraints in making test equipment and then establishment of the test methodology to be adopted took up considerable time and could not be completed in the phase 1 timescale.

No results are therefore available however mention should be made in regard to such tests which are important for the man on-site under the exposure conditions fresh concrete is subjected to in UAE.

3.1.8 Compression strength

Compression strength of all mixes tested in phase 1 trials (350kg cementitious content) is contained in **Chart 17** of **Appendix 9**.

The 28 days results for all groups were generally lower than typical results for Portland, GGBS and GGBS/MS commercial concretes possibly due to cement quality as one batch of cement was used throughout the phase 1 series.

Although strength at 28 days was rather low, strength gain for fly ash concretes was significant compared to other groups in the phase 1 series, as shown in **Table 7** on compressive strength gain from different cementing materials.

The 25 and 40% fly ash groups posted impressive gains between 7, 28, 56 and 90 days.

The 55% Fly ash mixes also gained strength significantly after 7 days from a much lower 7 day base.

3.1.9 Tensile and Flexural strength

High quality moulds for measurement of tensile strength could not be obtained locally during the period of the trials. Most sources of test equipment supplied Indian-made equipment which was found not to conform to international precision standards.

Tensile (Brazilian) test apparatus was also unable to be obtained as the test not routinely performed in UAE and apparatus required to be imported.

Consequently tensile and flexural strength was not measured in phases 1 and 2.

3.1.10 E - Values

These tests were not performed in phases 1 and 2 but may need to be carried out in commercial circumstances to obtain data on 80MPa pumpable mixes for LANDMARK project if required.

3.1.11 Durability properties

3.1.11.1 Initial surface absorption (BS 1881, part 122)

Initial surface absorption tests were carried out on each group of mixes at a binder content range of 200, 275, 350, 425 and 500kg of cementitious material.

Results of these tests with the exception of the Portland/GGBS/MS group (for which data appeared to be very unusual and therefore considered as null) are contained in **Chart 18 of Appendix 10**.

The results indicate that surface absorption characteristics of fly ash concretes are of further development interest based on initial findings, and further work, perhaps involving triple-blending of Microsilica may produce interesting values.

3.1.11.2 Rapid chloride permeability - ASTM C1202-97

Phase 1 rapid chloride permeability tests indicate that Fly Ash concrete is more permeable compared to Portland, Portland/GGBS and Portland/GGBS/MS blends.

25% Fly Ash mixes produced high RCP values relative to Portland and GGBS blends, at high cementitious levels, whilst 40 and 55% Fly Ash mixes have more satisfactory values at the same cementitious levels based on common local specification requirements (typically <1500 Coulombs).

The study also indicates that the use of small amounts of Microsilica in GGBS mixes appears to be of little value, which appears as contrary to local field test results.

3.1.11 Conclusions from Phase I

From phase 1 it was initially understood that the following properties and characteristics of fly ash concretes had been determined.

- Water demand at all fly ash replacement levels is satisfactory vs. Portland and GGBS reference concretes.
- With all fly ash mixes there is a lower density and modest net yield advantage after adjustment for lower water demand compared to other binder combinations.
- Fly Ash and GGBS concretes appear to have a minor slump retention disadvantage probably due to paste volume and choice of admixture, compared to Portland concretes.
- At 25% Fly Ash the final setting time is extended about 1 hour compared to Portland concretes.
- At 40% Fly Ash the final setting time is comparable to GGBS, with both mixes extending final set 3 hours compared to Portland concretes.
- Fly ash mixes have superior Low Heat properties, compared to other binder combinations used in phase 1 tests.
- Fly ash concrete strength gain is more pronounced than other groups

3.2 Results from Phase 2 trials

3.2.1 Water reduction

Using the revised admixture arrangement, significant water reduction was achieved in Phase 2, compared to Phase 1 trials. (Water demand of 13-15% of concrete volume, with WC ratios ≈ 0.3 and average slump of 225mm)

3.2.2 Slump

1 hour slump retention results of these mixes is contained in Appendix 12, Chart20

It can be observed from this Chart that slump retention of phase 2 mix designs using type D and F methodology has greatly improved vis-à-vis phase 1 mixes using Type G admixture, see **Table 8, Appendix 13, and original data is given in Table 9.**

Results of slump retention tests indicate that parameters set for LANDMARK requirements have been nominally met by all groups.

3.2.3 Compression strength

Compression strength results for each group are tabulated in **Table 10, Appendix 14**, in which the average cementitious content is 470kg/m³.

It can be observed from Table 7 that strength has improved markedly compared to phase 1 trials due to lower WC ratio and other admixture effects however early strength (40% group) and 28 day strength (all groups) does not meet internal criteria.

This was expected however and as it had already been assumed that Microsilica would be used to meet high performance and durability criteria

Further trials were carried out using 6% Microsilica and Fly Ash replacement levels of 25 and 40% together with the revised admixture methodology.

These further trials confirmed in both cases that high early and 28 day strength criteria can be met using low heat Fly Ash concretes and local (UAE) materials

The results can be observed in **Table 11, Appendix 14**.

4. FURTHER TESTS

Mention is previously made of non-standard tests for plastic settlement and shrinkage. Tests for these phenomena are non-standard.

Phase 1 properties which are recommended for further research are as follows;

- Tensile and flexural strength.
- E values for various compression strengths.
- Initial Surface Absorption (BS 1881, part 122).
- Rapid Chloride Permeability (Plain and triple blended Fly Ash mixes, using Microsilica).

Phase 2 properties which are recommended for further research are as follows;

- Slump retention, to 2 hours.
- Heat of Hydration of mass concrete
- Initial surface absorption - BS 1881, part 122
- Rapid Chloride Permeability - 28 and 56 days (ASTM C1202-97) for normal fly ash and triple blended Fly Ash mixes, incorporating Microsilica.
- 56 and 90 day strength of compression strength of normal fly ash and triple blended Fly Ash mixes, incorporating Microsilica.
- Tensile and flexural strength.
- E values for various compression strengths.
- Trial series repeated using Polycarboxylate admixtures

5. Field Test by Besix

The fly ash concrete of grade 40 and grade 50 was successfully used for raft foundation in Ferrari experience project by Besix. The mix design of fly ash concrete contains 25% fly ash and 15kg of silica fume in each cubic meters. The compressive strength and durability properties are satisfactory, as below:

Grade 50 fly ash concrete

- Compressive strength (MPa): 56 (28 days)
- Rapid chloride permeability (Coulombs): 793
- Water absorption (%): 1.7
- Water permeability (mm): 5

Grade 40 fly ash concrete

- Rapid chloride permeability (Coulombs): 798 (56 days)
- Water absorption (%): 1.76 (28days), 1.6 (56days)
- Water permeability (mm): 6.5 (33 days), 5.5 (56 days)

The collected test results on RCP at different ages are shown in **Appendix 15, Chart 21**.

As can be seen, the fly ash concrete presents satisfactory results by field sampling and testing.

6. CONCLUSIONS

Results demonstrate that fly ash concretes can be designed to produce results equivalent or superior to high performance Portland and blended GGBS high performance concretes in the UAE (at similar cost)

A quality assured source of Fly Ash should be used complying with the standards given in this report.

Admixture methodology is important when maximizing performance however normal type D and type F admixtures can produce excellent results.

28 day interpretations of performance may be waived in circumstances where later age testing permits users to take advantage lower heat of hydration and the superior strength gain of fly ash concretes.

Normal supplementary cement concretes set more slowly and are therefore appropriate for work where setting and hardening times are not critical - and good curing is essential to maximize benefits.

On the other hand, high performance concretes can be designed for special applications and in such cases; early strength can be comparable to that of Portland concretes.

The field testing results and application performance are satisfactory.

7. ACKNOWLEDGEMENTS

Many parties participated to enable this report to be completed.

A special acknowledgement is made of the efforts of Messrs. Anthony Ponge, and Alexander Le Clerke, French undergraduate students from Paris who worked tirelessly to learn about Concrete generally and in the UAE from starting positions of no knowledge.

Both students managed the many requirements for preparation, testing and documenting the work which was carried out under difficult circumstances, involving strenuous physical and mental work, very well indeed and are complimented on their efforts.

8. APPENDICES – Tables and charts

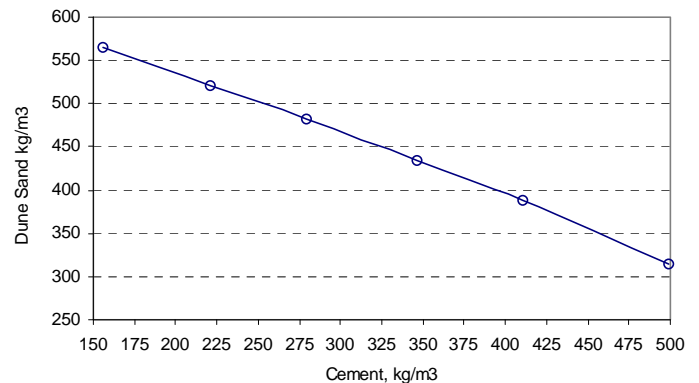
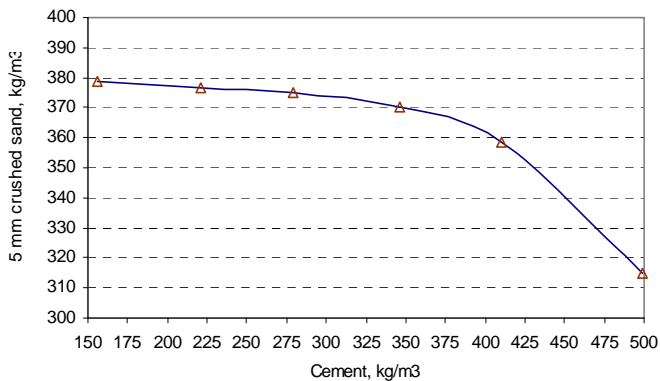
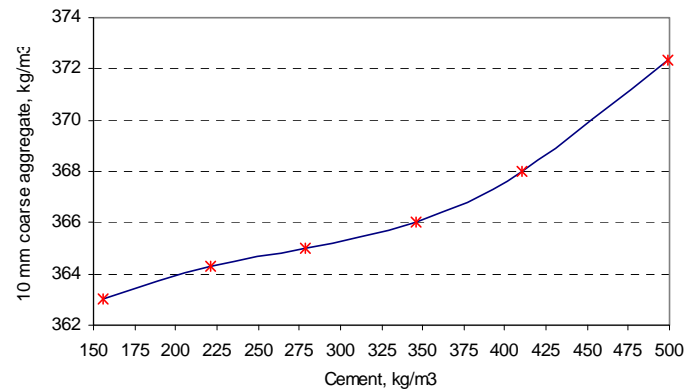
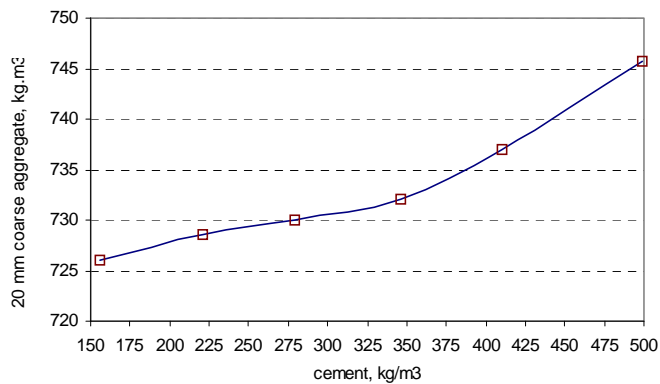
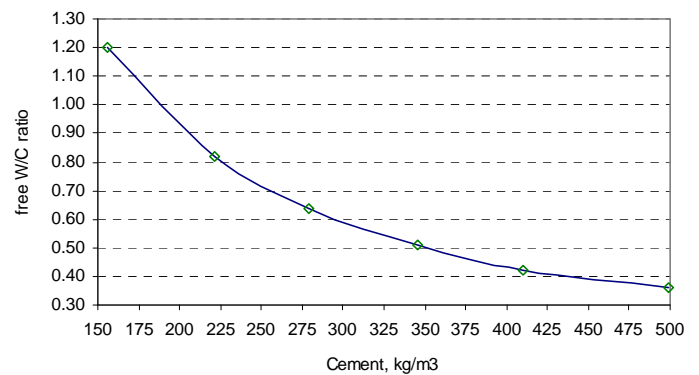
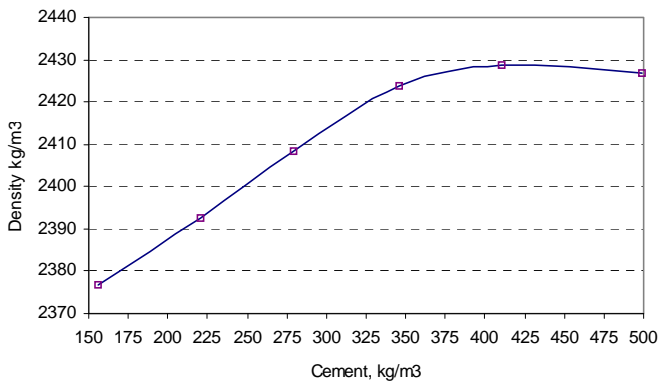
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Appendix 1 Pumpable trial series 2007

Table 1 - pumped concrete trials - 2007	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6
Portland Cement	156	221	279	346	410	499
20mm Crushed Limestone	726	729	730	732	737	746
10mm Crushed Limestone	363	364	365	366	368	372
5mm Crushed Limestone	379	377	375	370	359	315
Dune Sand	566	520	481	434	388	315
Free Water (FOSROC SP495 used at 1.2% BWC)	187	182	178	176	172	180
W/C	1.20	0.82	0.64	0.51	0.42	0.36
Plastic density	2377	2392	2409	2424	2429	2427

Chart 1 Design parameters vs cement quantity



Appendix 2, Table 2 –Benchmark mix design for Phase 1

Portland reference mixes	Portland Cement	Limestone aggregates			Dune sand	FOSROC SP495 Type G admixture	Notional Free Water	Notional plastic density	Notional AC ratio	Notional WC ratio
		20mm	10mm	<5mm						
Mix 1	200	728	364	378	542	2.4	175	2389	10.06	0.88
Mix 2	275	730	365	375	487	3.6	172	2408	7.12	0.63
Mix 3	350	732	366	370	434	4.8	170	2427	5.43	0.49
Mix 4	425	738	368	350	385	6	172	2444	4.33	0.40
Mix 5	500	745	372	316	320	7.2	175	2435	3.51	0.35

Notes

For GGBS:

Portland content is substituted by 65% GGBS

For GGBS/Microsilica:

Portland content is substituted by 60% GGBS and 10kg of Microsilica is added to the total cementitious content (RCP compliance testing)

For 25% Fly Ash:

Portland content is substituted by 25% Fly Ash

For 40% Fly Ash:

Portland content is substituted by 40% Fly Ash

For 55% Fly Ash:

Portland content is substituted by 55% Fly Ash

Appendix 2, Table 3 - Phase 1 trial final mix proportions (after yield correction)

Test Group	Cement	Supplementary Cement	20mm	10mm	5mm	Dune Sand	Admixture	Water	Measured Plastic Density	AC ratio/1	WC ratio
Portland control mixes											
Mix 1	192	0	717	359	369	530	2.20	172	2341	10.26	0.89
Mix 2	269	0	722	361	367	479	2.95	168	2369	7.18	0.63
Mix 3	343	0	711	356	367	421	3.88	172	2374	5.41	0.50
Mix 4	417	0	722	361	342	376	4.89	168	2391	4.32	0.40
Mix 5	499	0	744	372	314	318	5.97	170	2425	3.50	0.34
Average Portland mix	344	0	723	362	352	425	3.93	170	2380	5.41	0.49
Portland GGBS mixes											
Mix 1	69	128	715	358	372	529	1.94	172	2344	10.02	0.87
Mix 2	95	177	722	361	371	479	2.93	168	2376	7.11	0.62
Mix 3	120	224	719	359	363	424	3.90	167	2379	5.43	0.49
Mix 4	146	270	720	360	343	369	4.89	171	2384	4.31	0.41
Mix 5	172	329	750	375	314	310	5.94	172	2428	3.49	0.34
Average GGBS mix	120	226	725	363	353	422	3.92	170	2382	5.39	0.49
Portland GGBS/MS mixes (GGBS + 10kg MS)											
Mix 1	71	125	714	357	376	518	1.88	171	2334	10.00	0.87
Mix 2	103	172	713	357	365	483	2.92	166	2362	6.97	0.60
Mix 3	124	212	730	365	359	417	3.78	163	2372	5.57	0.48
Mix 4	162	255	708	354	335	380	4.82	170	2367	4.26	0.41
Mix 5	191	303	734	367	314	309	5.88	172	2395	3.49	0.35
Average GGBS/MS mix	130	213	720	360	350	421	3.86	168	2366	5.39	0.49
25% Fly Ash											
Mix 1	143	48	695	347	361	513	1.88	167	2277	10.04	0.88
Mix 2	202	67	716	358	368	475	2.93	167	2355	7.12	0.62
Mix 3	256	86	713	356	359	420	3.90	166	2360	5.41	0.48
Mix 4	309	103	716	358	340	366	4.84	165	2363	4.32	0.40
Mix 5	368	123	730	365	309	313	5.88	172	2383	3.50	0.35
Average 25% FA mix	256	85	714	357	347	417	3.88	167	2348	5.39	0.49
40% Fly Ash											
Mix 1	118	79	715	358	372	529	1.93	162	2335	10.04	0.82
Mix 2	163	109	719	359	369	476	2.94	158	2356	7.09	0.58
Mix 3	206	136	716	358	361	422	3.90	156	2359	5.43	0.46
Mix 4	249	166	721	360	342	369	4.87	152	2364	4.31	0.37
Mix 5	294	196	730	365	309	313	5.88	162	2375	3.50	0.33
Average 40% FA mix	206	137	720	360	351	422	3.90	158	2358	5.40	0.46
55% Fly Ash											
Mix 1	89	109	720	360	374	533	1.93	153	2339	10.06	0.78
Mix 2	123	150	726	363	373	482	2.94	144	2364	7.12	0.53
Mix 3	155	189	722	361	364	425	3.88	142	2362	5.44	0.41
Mix 4	186	229	721	361	343	370	4.81	142	2357	4.32	0.34

Appendix 3

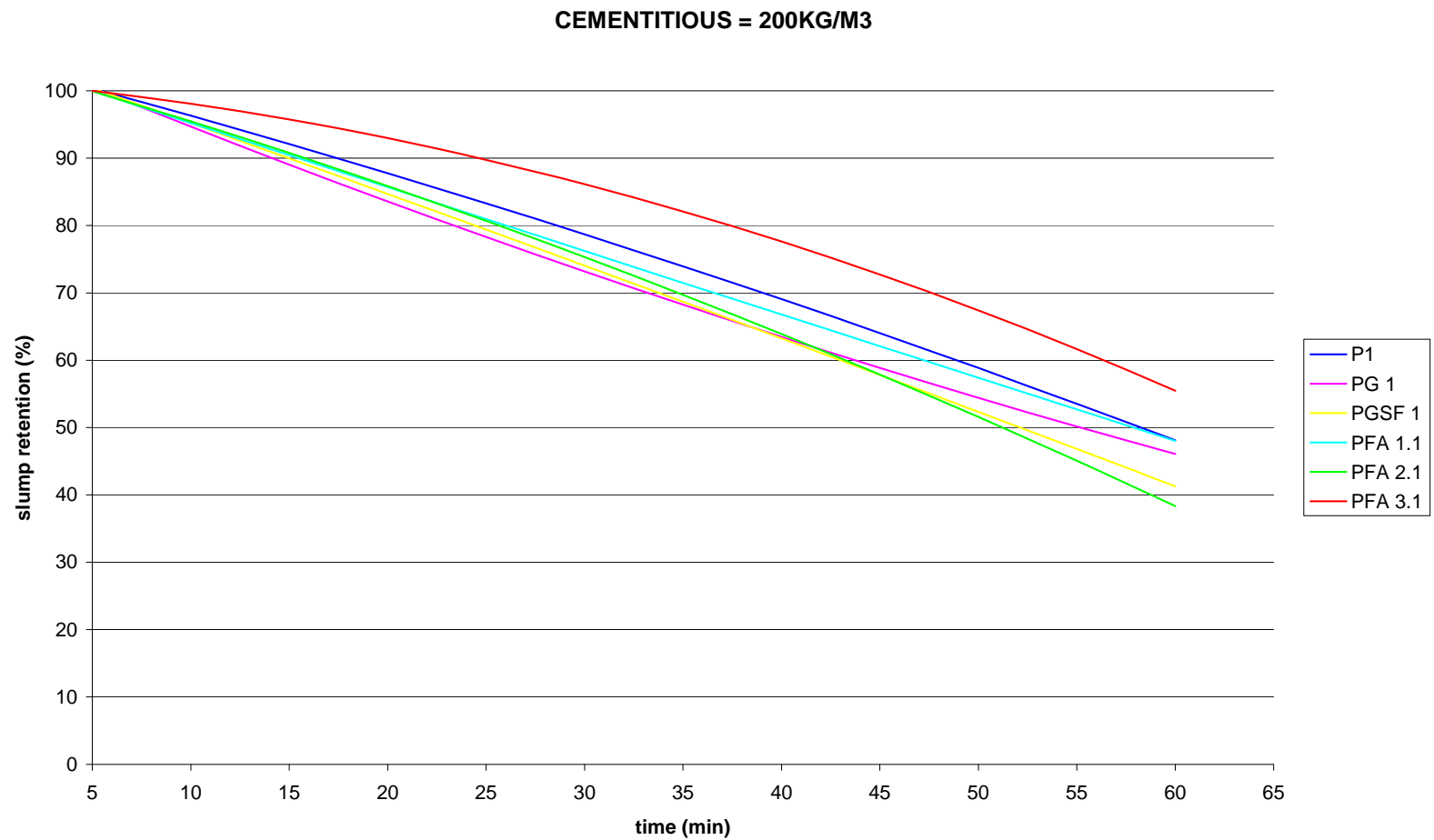
Testing program for EcoSmart Project

Table 4 – Test contents on the concretes for ECOSMART project

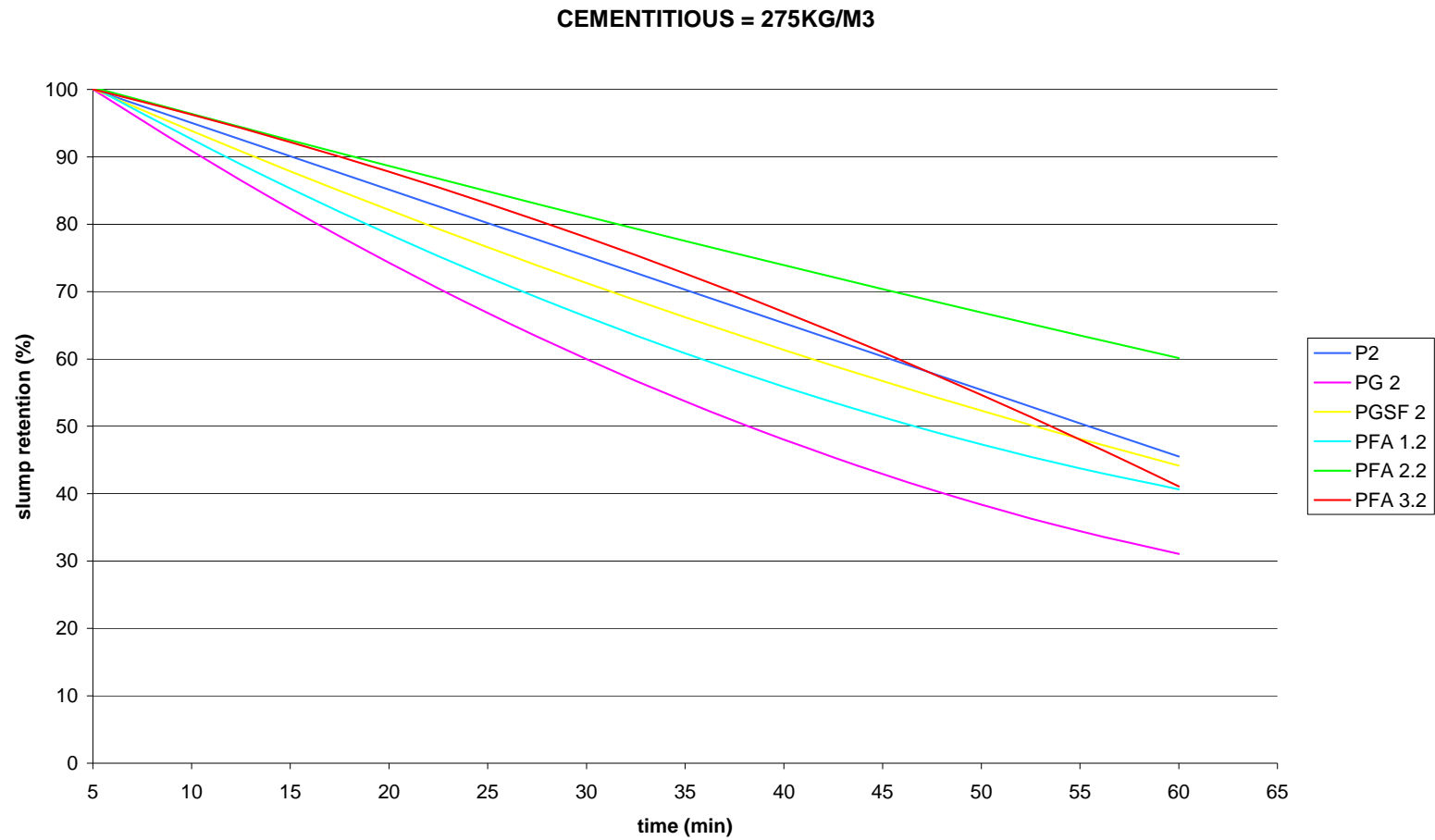
Parameter/property	Testing standards and comments
Trial water demand	Gradual addition to required slump and measurement
Slump	British/universal standard
Plastic density and final mix proportions	British/universal standard
Slump retention	British/universal standard - slump tested at 15 minute intervals
Setting time	ASTM C403
Heat of hydration	Insulated samples tested using data logger and proprietary software
Bleeding, finishability, pumpability	Visually assessed, not evaluated via testing
Compression	British/universal standard
Initial surface absorption	BS 1881, Part 122
Rapid chloride permeability	ASTM C1202

Phase 1 Mix design: 30 mixes: with 6 Cementing material combinations and 5 Cementing material levels

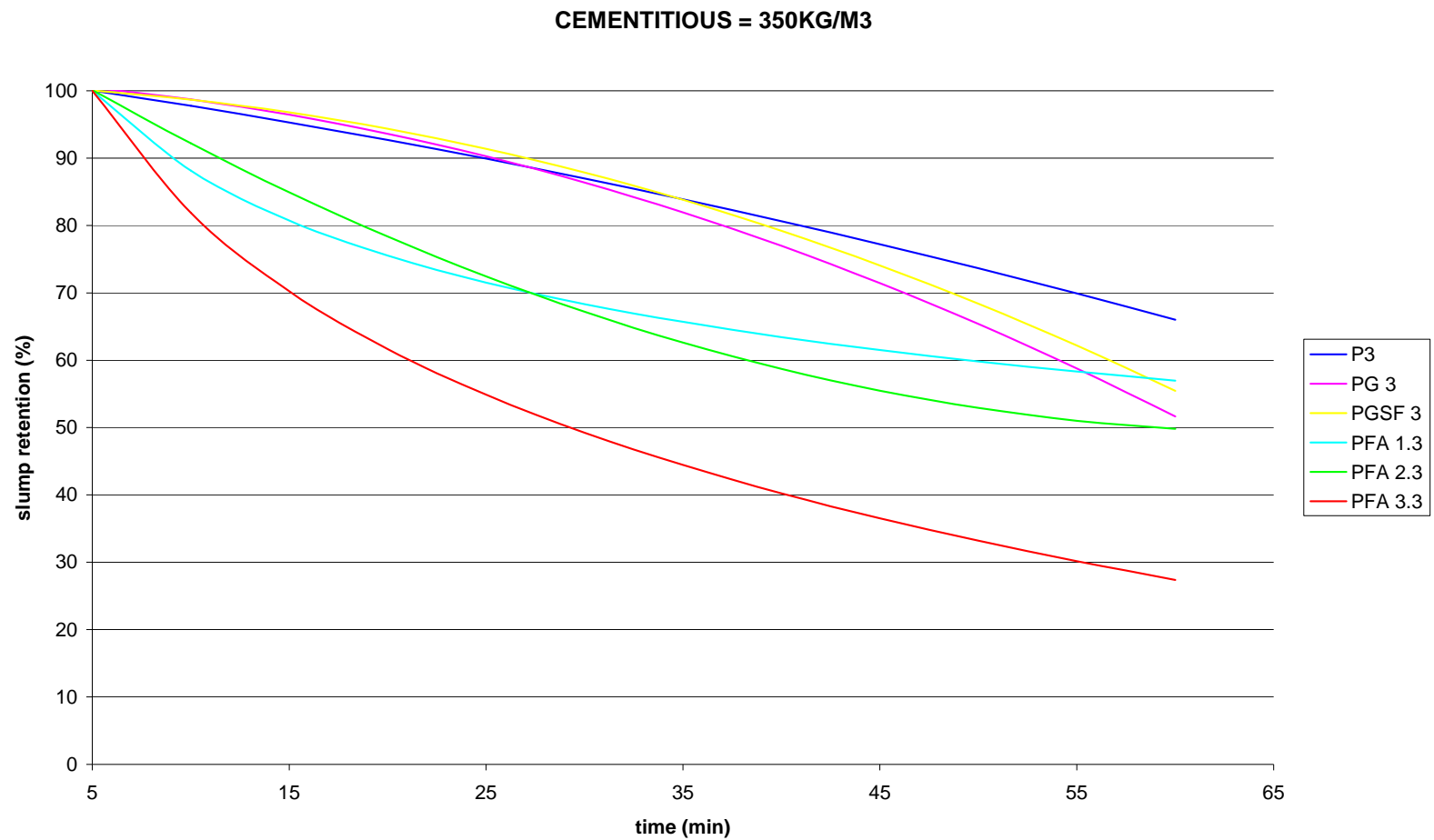
Phase 2 Mix design: 12 mixes: with 3 FA levels and 4 Cementing material levels



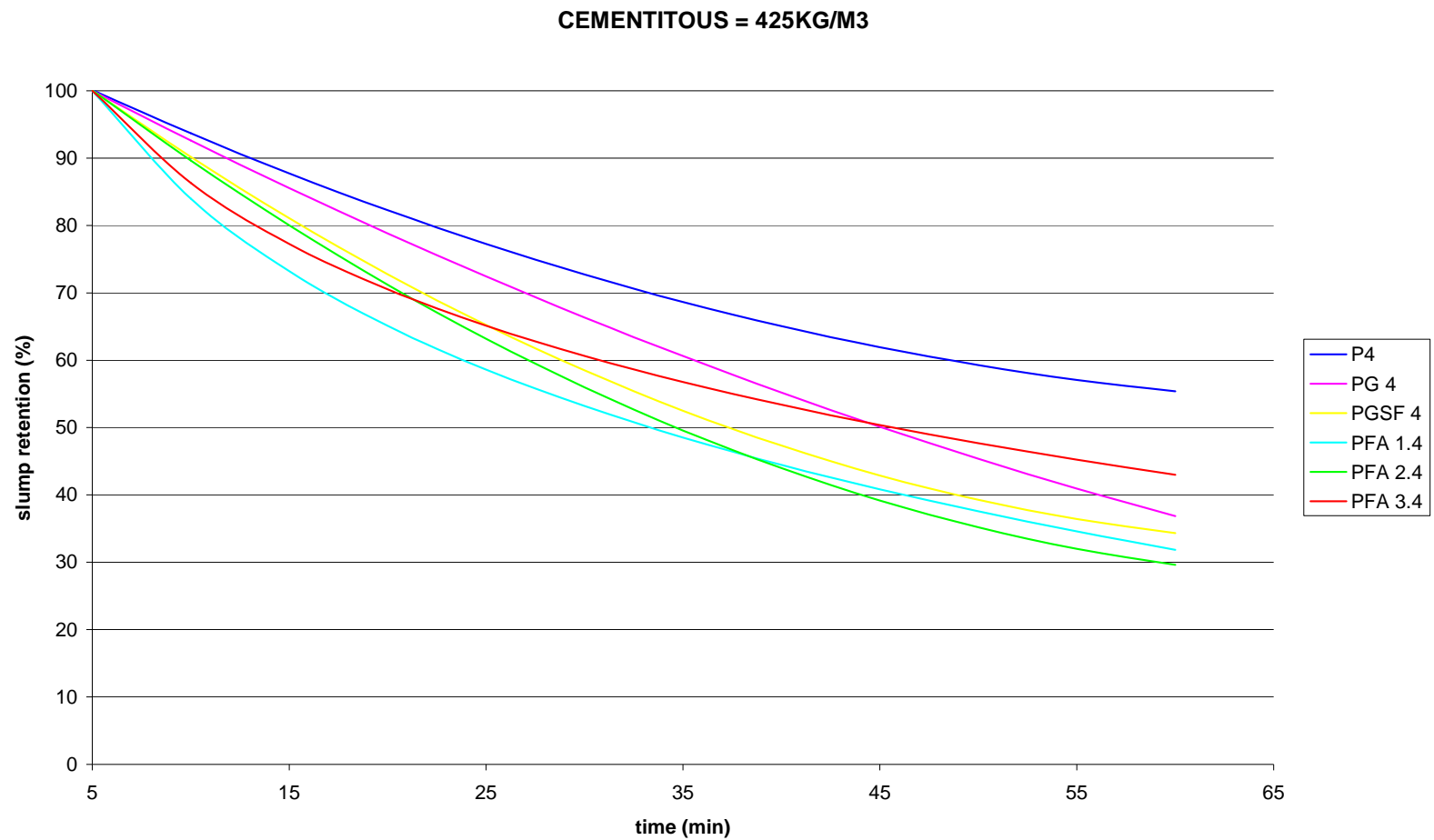
Appendix 4 Chart 2-1 Slump retention (Phase 1-Cementitious at 200 kg/m3)



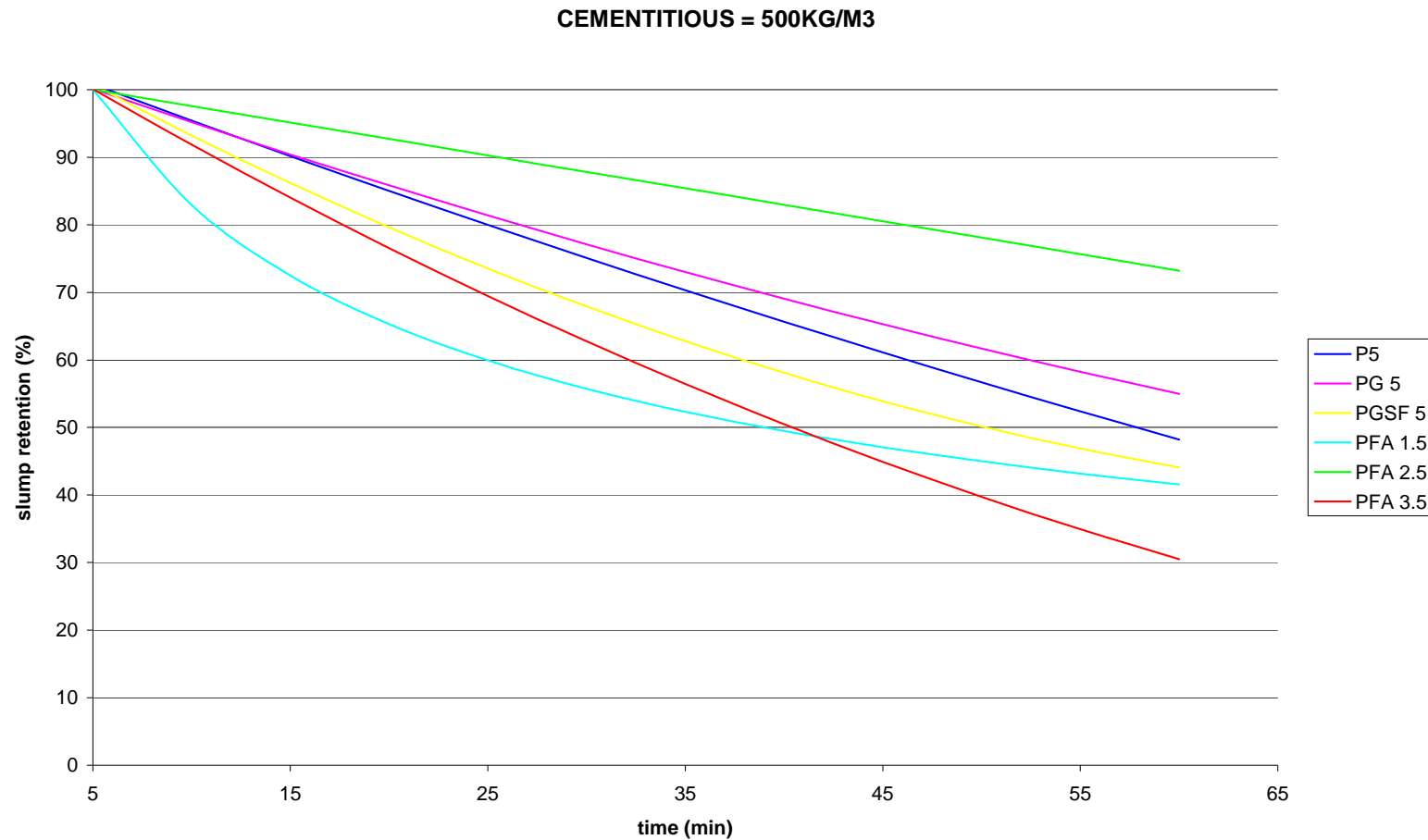
Appendix 4 Chart 2-2 Slump retention (Phase 1-Cementitious at 275 kg/m3)



Appendix 4 Chart 2-3 Slump retention (Phase 1-Cementitious at 350 kg/m3)



Appendix 4 Chart 2-4 Slump retention (Phase 1-Cementitious at 420 kg/m3)



Appendix 4 Chart 2-5 Slump retention (Phase 1-Cementitious at 500 kg/m3)

APPENDIX 4

Table 5 Slump and slump retention of phase 1 fly ash concretes

Name	Time elapsed	Slump	Slump retention
P1	5	155	100.00
	22	135	87.10
	37	110	70.97
	57	80	51.61
	67		
P2	9	135	100.00
	20	120	88.89
	35	100	74.07
	50	80	59.26
	65	60	44.44
P3	5	150	100.00
	20	135	90.00
	35	125	83.33
	50	110	73.33
	65	90	60.00
P4	10	145	100.00
	20		
	35	105	72.41
	50	90	62.07
	65	80	55.17
P5	10	145	100.00
	20	125	86.21
	35	105	72.41
	54	85	58.62
	65	65	44.83
PG1	7	155	100.00
	20	130	83.87
	35	105	67.74
	50	90	58.06
	65	65	41.94
PG2	9	165	100.00
	20	130	78.79
	35	98.5	59.70
	50	67.5	40.91
	65	50	30.30
PG3	10	160	100.00
	20	150	93.75
	35	135	84.38
	50		

	65	75	46.88
PG4	10	150	100.00
	30		
	39	92.5	61.67
	50	75	50.00
	65	55	36.67
PG5	10	220	100.00
	20	195	88.64
	35	170	77.27
	50	120	
	65	120	54.55
PGSF 1	5	140	100.00
	20	120	85.71
	35	95	67.86
	50	90	
	65	50	35.71
PGSF 2	5	140	100.00
	20	120	85.71
	35	95	67.86
	50	70	50.00
	65	60	42.86
PGSF 3	5	150	100.00
	20	140	93.33
	35	125	83.33
	55	80	
	65	70	46.67
PGSF 4	10	150	100.00
	26	100	66.67
	35	90	60.00
	50	65	43.33
	65	50	33.33
PGSF 5	10	150	100.00
	20	140	93.33
	43	90	60.00
	50	80	53.33
	70	65	43.33
PFA 1.1	10	145	100.00
	20	130	89.66
	35	110	75.86
	50	90	62.07
	64	70	48.28
PFA 1.2	8	145	100.00
	20	115	79.31
	35	90	62.07
	50	75	51.72

	65	55	37.93
PFA 1.3	10	145	100.00
	20	110	75.86
	40	95	65.52
	50	90	62.07
	65	82.5	56.90
PFA 1.4	8	155	100.00
	20	110	70.97
	35	75	48.39
	50	70	
	65	50	32.26
PFA 1.5	10	175	100.00
	20	130	74.29
	35	100	57.14
	50	85	48.57
	65	70	40.00
PFA 2.1	13	155	100.00
	20	140	90.32
	35	125	80.65
	50	90	58.06
	65	65	41.94
PFA 2.2	6	155	100.00
	20	140	90.32
	35	120	77.42
	50	105	67.74
	69	85	54.84
PFA 2.3	13	157	100.00
	22	140	89.17
	35	110	70.06
	50	90	57.32
	65	80	50.96
PFA 2.4	12	145	100.00
	20	125	86.21
	35	85	58.62
	50	60	41.38
	65	45	31.03
PFA 2.5	10	145	100.00
	20	125	86.21
	35	115	79.31
	53	80	55.17
	67	50	34.48
PFA 3.1	10	150	100.00
	20	145	96.67
	35	130	86.67
	50	110	73.33

	65	85	56.67
PFA 3.2	7	165	100.00
	20	150	90.91
	35	95	
	52	90	54.55
	66	60	36.36
PFA 3.3	7	190	100.00
	17	130	68.42
	32	90	47.37
	47	75	39.47
	62	50	26.32
PFA 3.4	8	150	100.00
	20	105	70.00
	35	90	60.00
	53	75	50.00
	66	60	40.00
PFA 3.5	9	210	100.00
	20	155	73.81
	35	125	59.52
	50	96	45.71
	65	55	26.19

Appendix 6, Charts 9-10, Setting times of various binders

Chart 9 Comparative setting time of various binder combinations (ASTM C403)

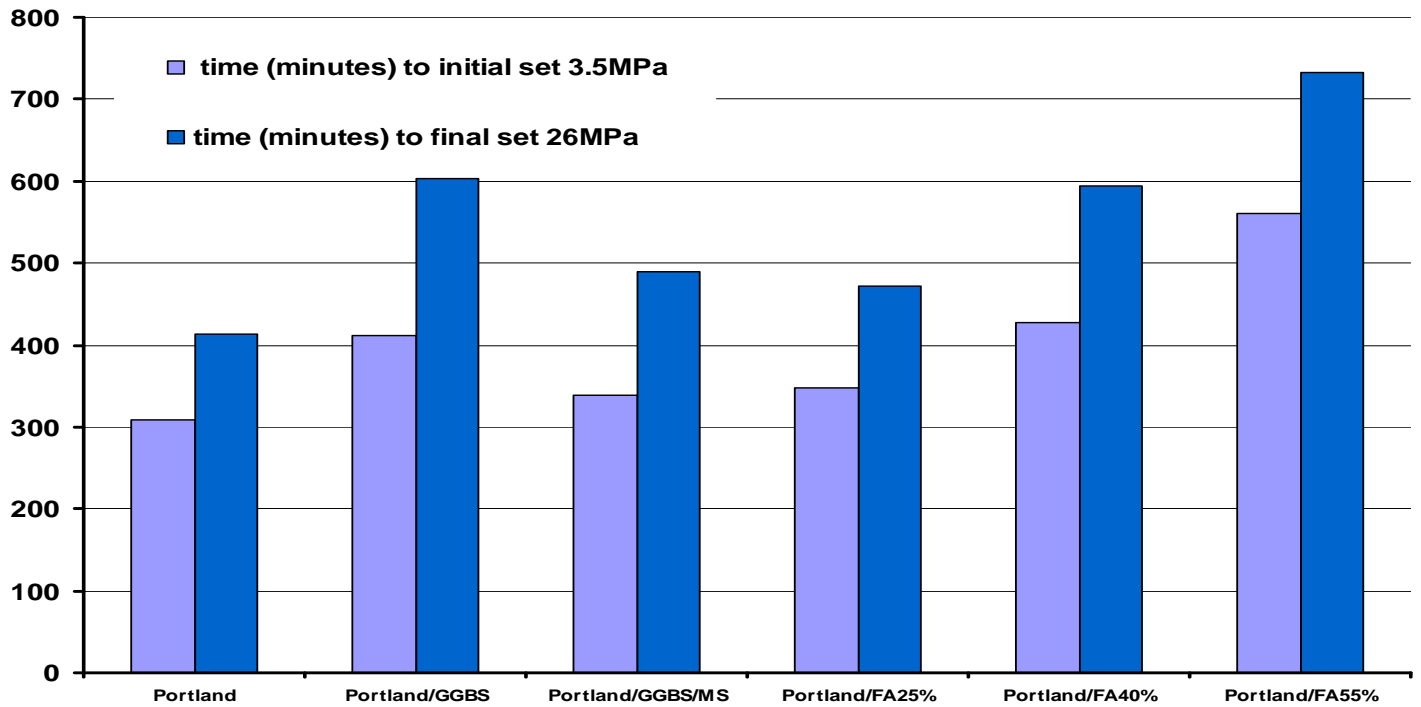
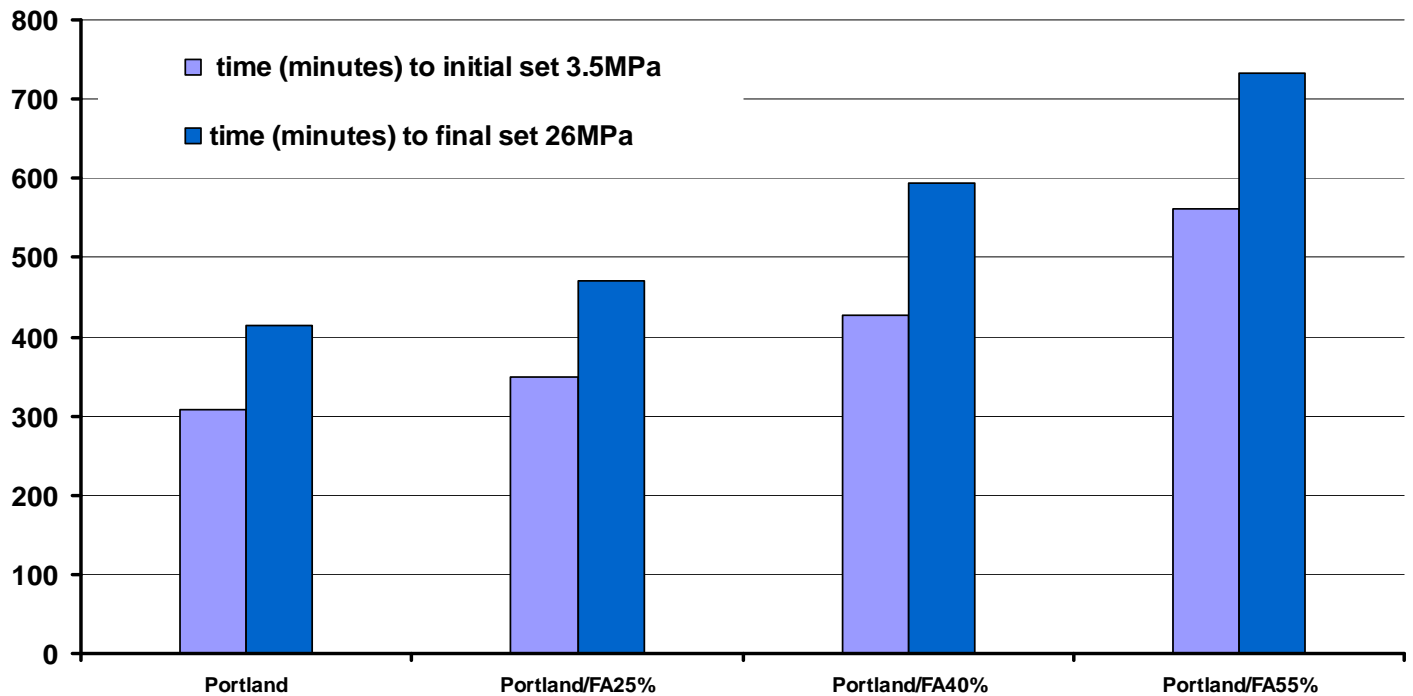


Chart 10 Comparative setting time of Portland and Portland-fly ash blends (ASTM C403)



Appendix 7, Table 6 - Heat of hydration tests on various binder combinations

Group/Mix	Binder/s	Binder total kg/m ³	Maximum (°C) *	ΔT (°C)	ΔT/ cementitious °C/100 Kg	ΔT/ cementitious °C/100 Kg - group	Time to maximum temperature and average time (group)		Total °C cumulative at 5 min. intervals over 62hrs	Total °C (group)
P3	100% OPC	350	44.8	19.8	5.7	5.83	17:00:00	16:40:00	28875	91490
P4		425	48.9	23.9	5.6		17:00:00		30767	
P5		500	55.7	30.7	6.1		16:00:00		31848	
PG3	65% GGBS 35% OPC	350	38.6	13.6	3.9	3.85	33:40:00	32:11:40	25443	78652
PG4		425	41.3	16.3	3.8		29:05:00		26296	
PG5		500	44.2	19.2	3.8		33:50:00		26914	
PGSF 3	10Kg SF 65% GGBS 35% OPC	350	34.4	9.4	2.7	2.59	30:15:00	29:55:00	26271	83355
PGSF 4		425	39.3	14.3	3.4		31:00:00		27687	
PGSF5		500	46.7	21.7	4.3		28:30:00		29397	
25% FA 3	25% Fly Ash	350	42.6	17.6	5.0	4.79	21:10:00	21:36:40	27073	85201
25% FA 4		425	44.4	19.4	4.6		21:05:00		28035	
25% FA 5		500	49.1	24.1	4.8		22:35:00		30093	
40%FA 3	40% Fly Ash	350	36.8	11.8	3.4	3.53	20:05:00	21:36:40	25039	79029
40%FA 4		425	39.6	14.6	3.4		20:25:00		25712	
40%FA.5		500	43.6	18.6	3.7		24:20:00		28278	
55%FA.3	55% Fly Ash	350	33.0	8.0	2.3	2.62	31:55:00	30:53:20	22423	71733
55%FA 4		425	36.0	11.0	2.6		29:50:00		24176	
55%FA 5		500	39.4	14.4	2.9		30:55:00		25134	

Notes - Temperature at time of mixing is 25±1°C, numbering of mix design series given above - “3” denotes cementitious content of 350kg/m³, “4” denotes cementitious content of 425kg/m³, “5” denotes cementitious content of 500kg/m³ (Includes Microsilica where applicable).

Appendix 8, Charts 11-16 - Comparison of evolution of heat of hydration of various binder combinations in C° over 60 hours

(Mixes containing 350, 425 and 500kg of cementitious material per cubic metre)

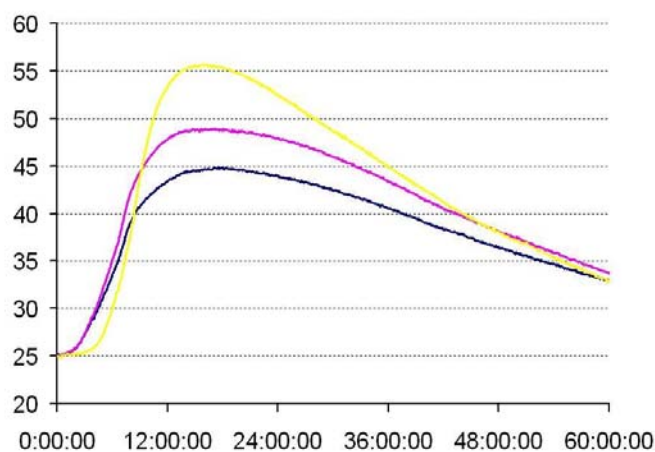


Chart 11 - Portland mixes

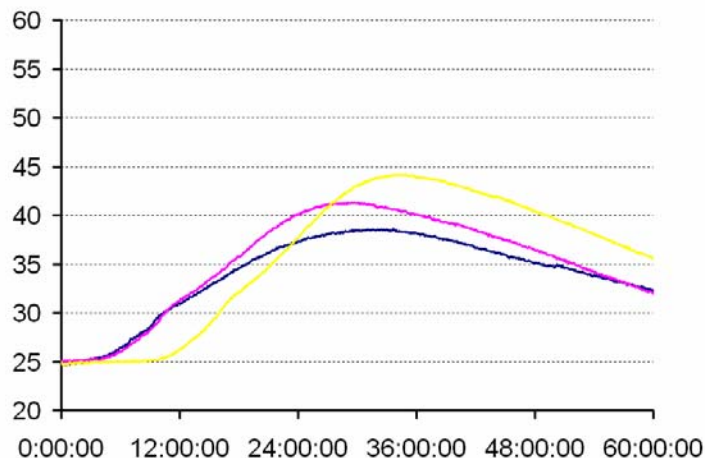


Chart 12 - Portland/GGBS mixes

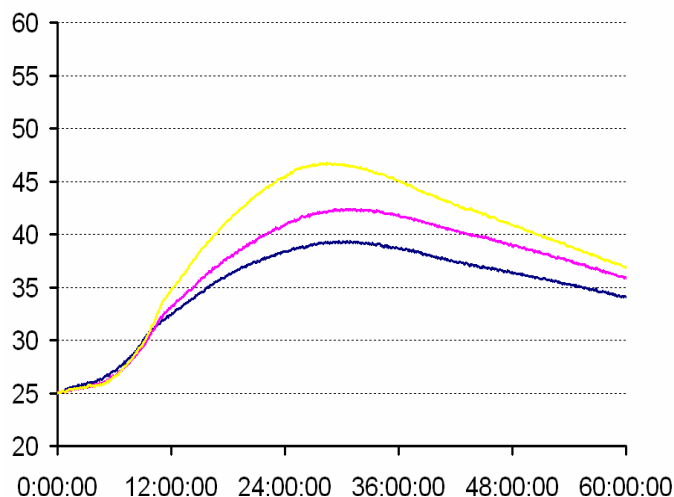


Chart 13 - PortlandGGBS/MS mixes

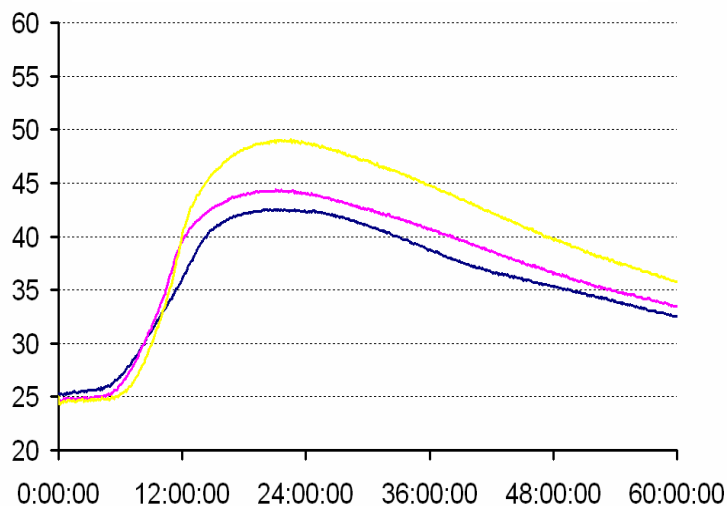


Chart 14 - Portland/25% Fly Ash mixes

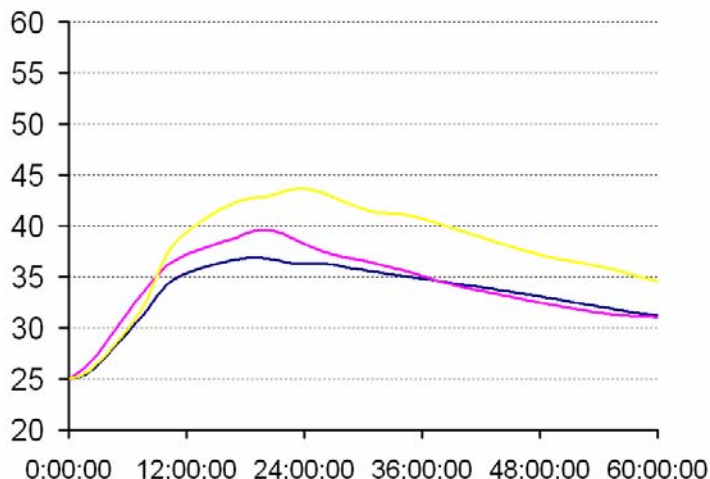


Chart 15 - Portland/40% Fly Ash mixes

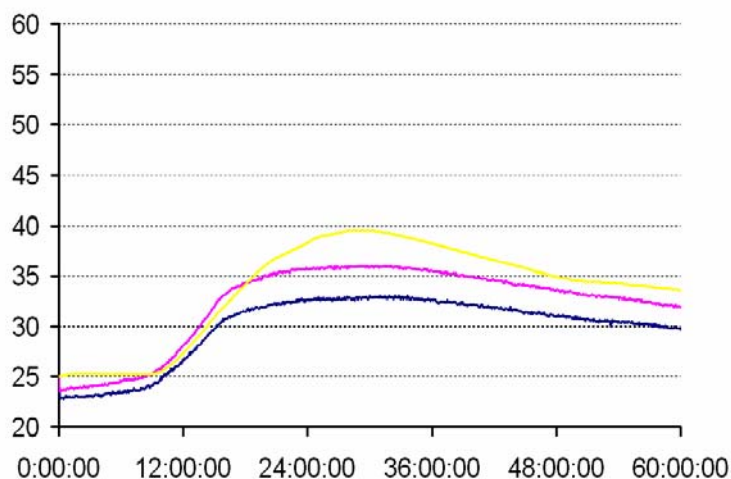
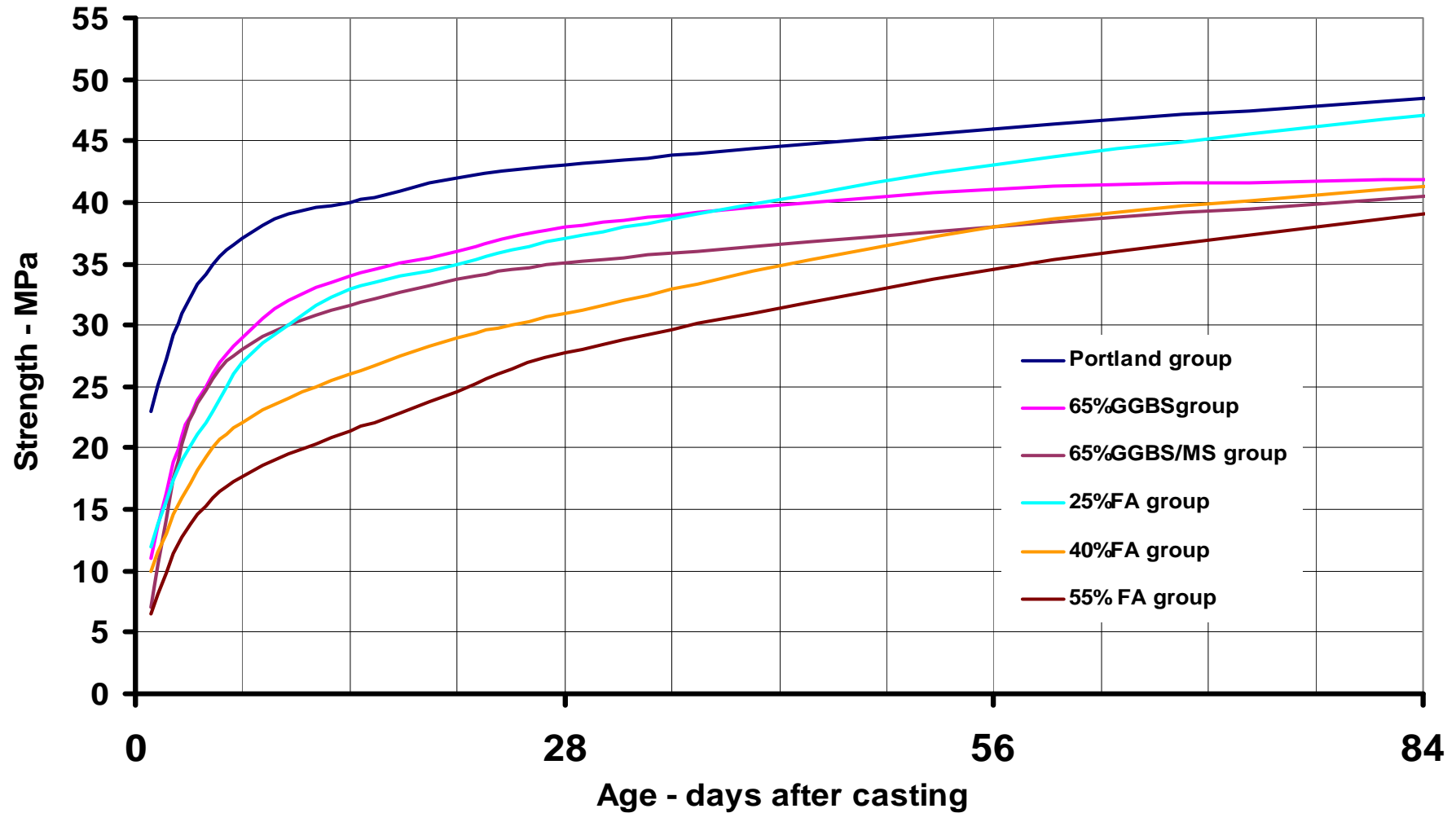


Chart 16 - Portland/55% Fly Ash mixes

Compression strength of various binders (350kg cementitious content)

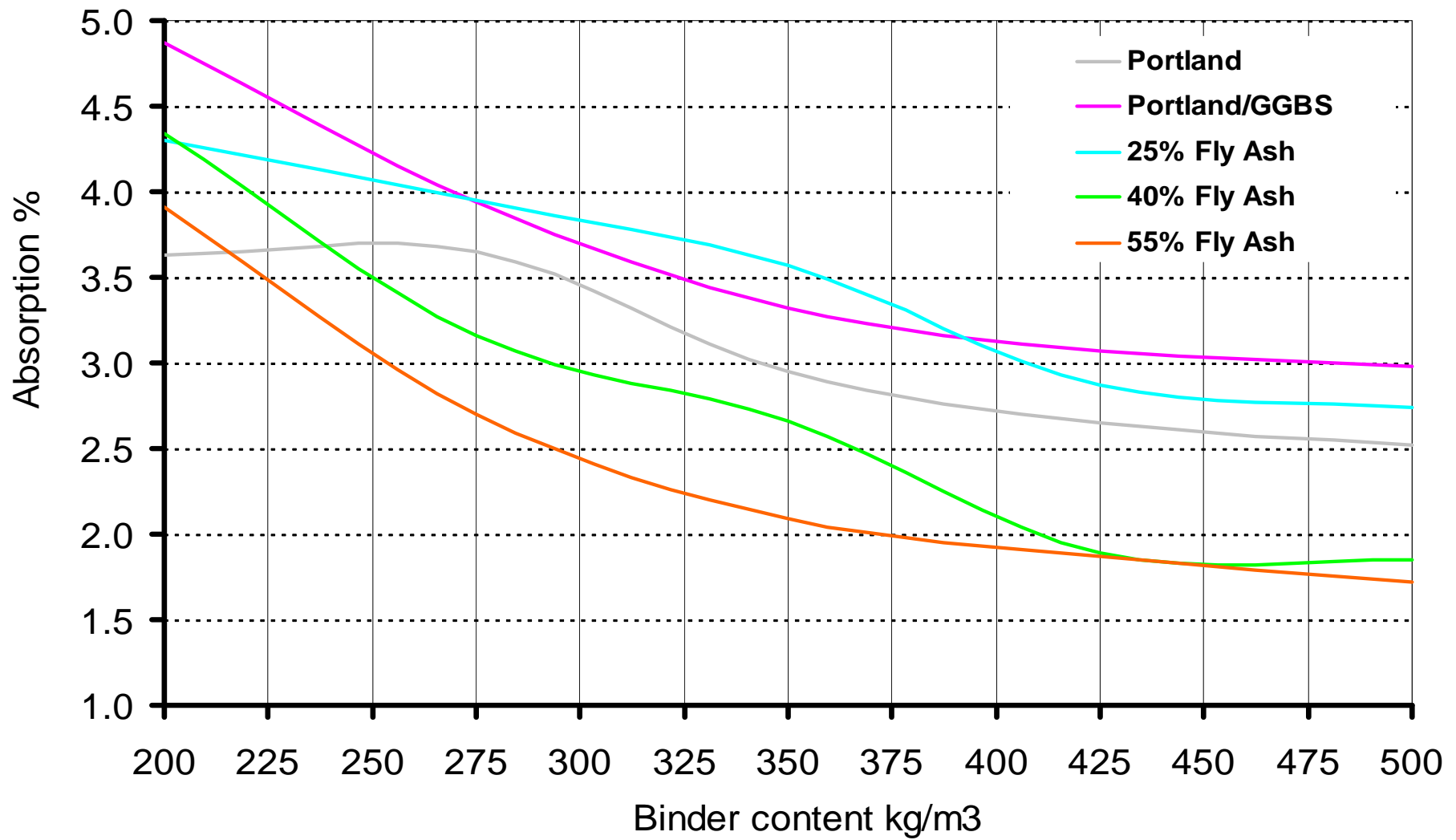


Appendix 9, Chart 17 - Compression strength of various binders (Phase 1 test series)

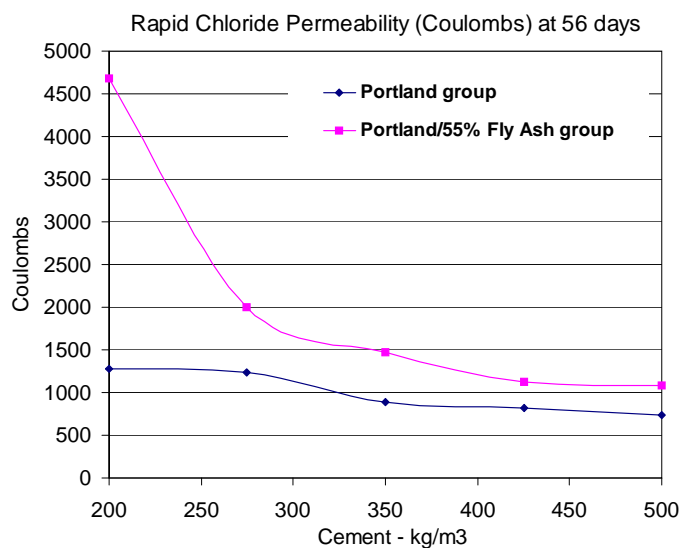
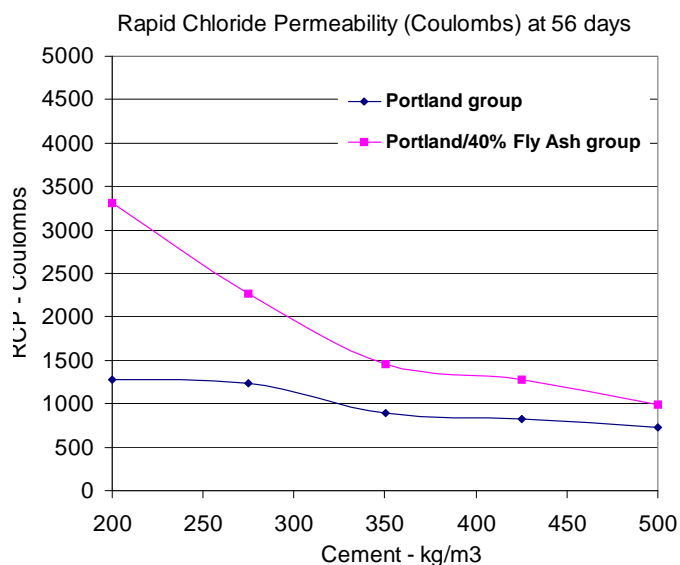
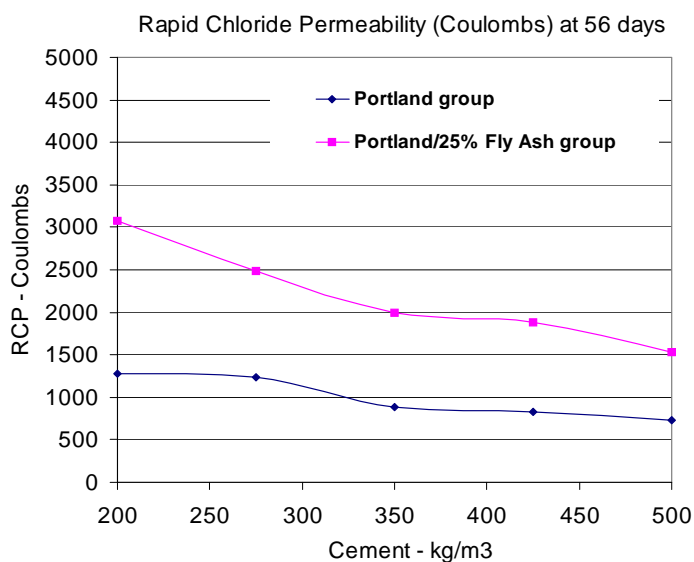
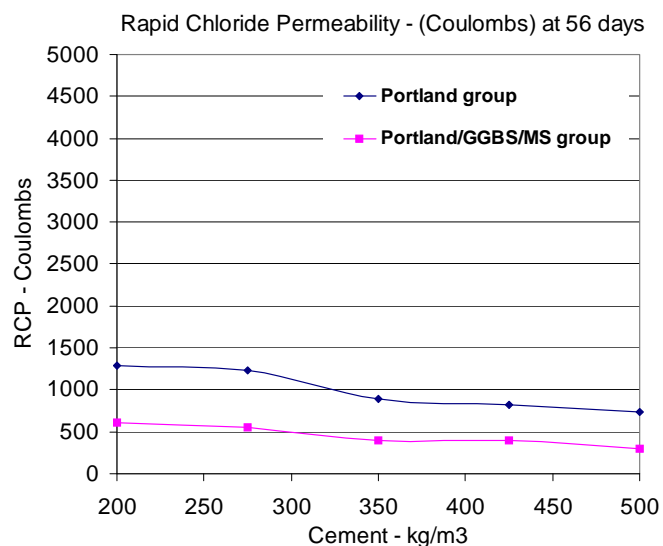
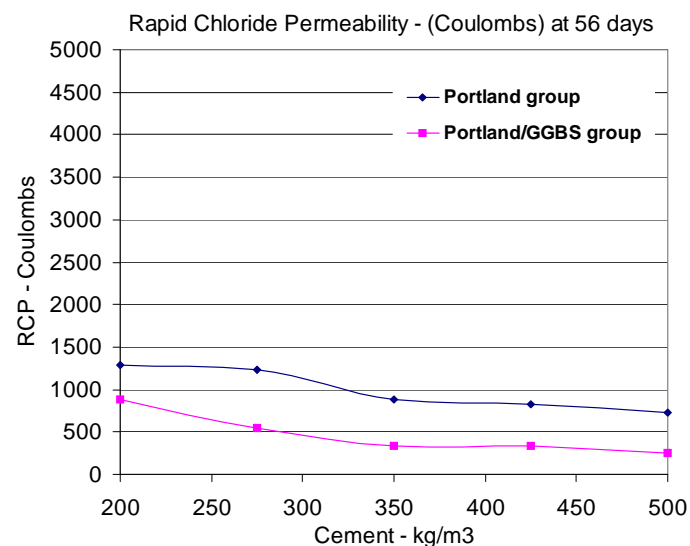
Appendix 9

Table 7 Compressive strength gain from different cementing materials

Cementing materials	Compressive strength gain, MPa		
	7-28 days	28-56 days	56-90 days
OPC	6	3	6
65% GGBS	9	3	4
65% GGBS+MS	7	3	2.5
25% FA	10	6	11
40% FA	9	7	11
55% FA	10	7	12

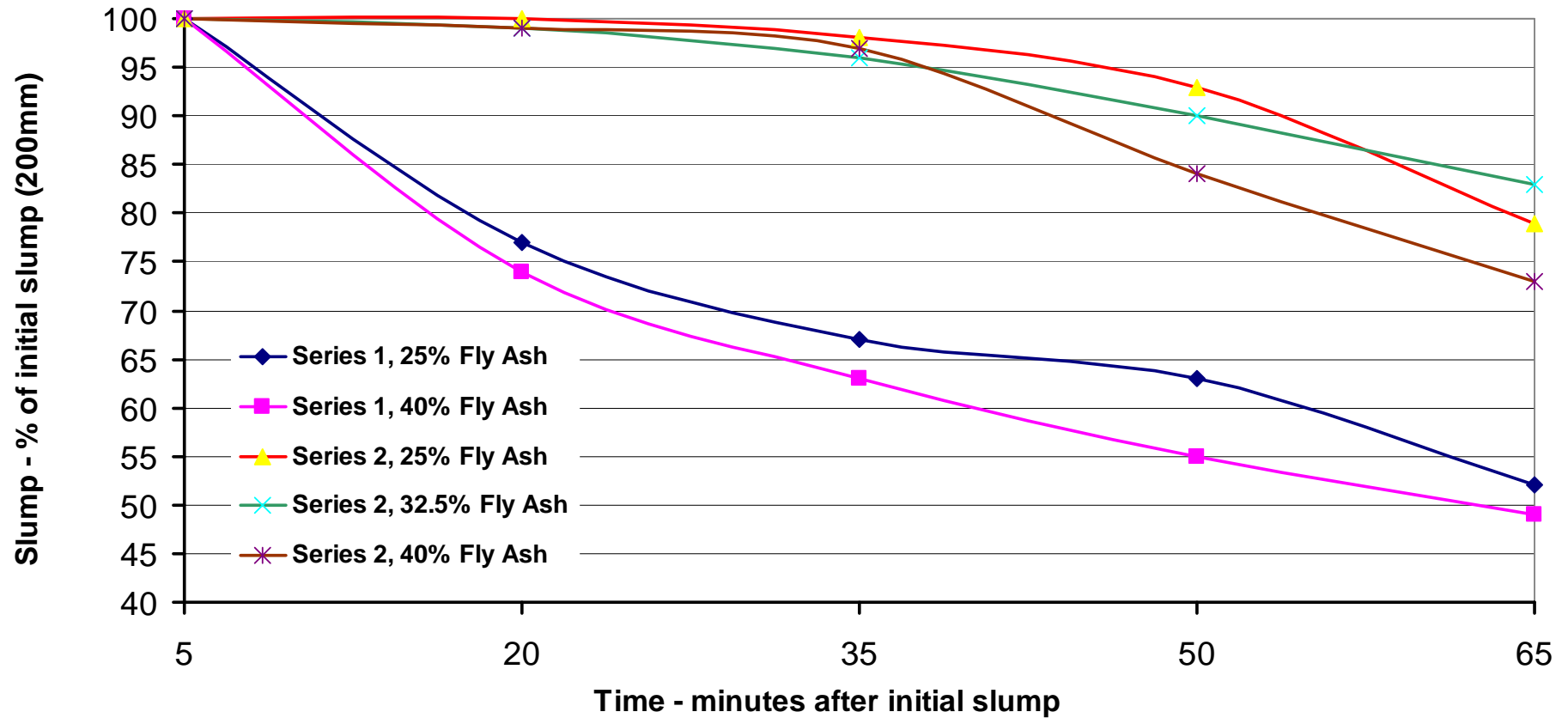


Appendix 10, Chart 18 - Initial surface absorption of various binders (BS 1881, part 122)



Appendix 11, Chart 19 - Rapid Chloride Permeability tests on various binders
 (ASTM C1202-97)

1 hour slump retention - comparison of phase 1 and 2 trial series.
(nominal cementitious content 470kg/m³)



Appendix 12, Chart 20 - Comparison of slump retention of various fly ash mixes, tested in phase 1 and 2 trials

(Nominal cementitious content 470kg/m³)

Appendix 13, Slump and slump retention for Phase 2 Mixes

Table 8 Slump test for various fly ash trial groups in Phase 2

Fly ash mix design	Slump, percent of initial slump				
	5min	20min	35min	50min	65min
25% group average result	100	100	98	93	79
32.5% group average result	100	100	96	90	83
40% group average result	100	100	97	84	73

Table 9 Original slump and slump retention of Phase 2 fly ash concrete

Name	Time elapsed	Slump	Slump retention
PFA 4.1 (FA25)	0	250	100.00
	15	250	100.00
	30	245	98.00
	45	215	86.00
	60	110	44.00
PFA 4.2 (FA25)	0	250	100.00
	15	250	100.00
	30	250	100.00
	45	240	96.00
	60	210	84.00
PFA 4.3 (FA25)	0	250	100.00
	15	250	100.00
	30	240	96.00
	35	230	92.00
	50	190	76.00
PFA 4.4 (FA25)	0	250	100.00
	15	250	100.00
	30	250	100.00
	31	249	99.60
	60	210	84.00
PFA 4.5 (FA25)	0	250	100.00
	15	250	100.00
	25	245	98.00
	35	205	82.00
	45	110	44.00
PFA 5.1 (FA32.5)	0	250	100.00
	60	250	100.00
	75	240	96.00
	90	210	84.00
	110	105	42.00
	0	250	100.00

PFA 5.2 (FA32.5)	30	250	100.00
	60	250	100.00
	61	249	99.60
	75	200	80.00
	90	120	48.00
PFA 5.3 (FA32.5)	0	250	100.00
	15	250	100.00
	30	250	100.00
	45	240	96.00
	75	145	58.00
PFA 5.4 (FA32.5)	0	250	100.00
	15	250	100.00
	30	230	92.00
	45	205	82.00
PFA 5.5 (FA32.5)	0	260	100.00
	15	260	100.00
	40	260	100.00
	41	259	99.62
	60	215	82.69
	70	190	73.08
	95	95	36.54
PFA 6.1 (FA40)	0	250	100.00
	15	250	100.00
	40	245	98.00
	56	200	80.00
	65	110	44.00
PFA 6.2 (FA40)	0	250	100.00
	15	250	100.00
	30	230	92.00
	45	140	56.00
PFA 6.3 (FA40)	0	250	100.00
	15	250	100.00
	30	250	100.00
	44	250	100.00
	45	250	100.00
	50	245	98.00
	60	220	88.00
PFA 6.4 (FA40)	0	250	100.00
	30	250	100.00
	45	245	98.00
	60	220	88.00
	75	130	52.00
PFA 6.5 (FA40)	0	250	100.00
	15	250	100.00
	28	250	100.00
	30	249	99.60
	45	230	92.00

APPENDIX 14

Table 10 Compression strength of fly Ash mixes from Phase 2 trials

Fly ash mix design	Compression strength, MPa			
	1 day	3days	7days	28days
25% group average result	21	48	63	85
32.5% group average result	13	43	59	78
40% group average result	8	39	54	75

Table 11 Compression strength of durability group with microsilica

Fly ash mix design	Compression strength, MPa			
	1 day	3 days	7days	28 days
25% Fly Ash, 520kg, 6% MS	20	52	75	114
40% Fly Ash, 500kg, 6% MS	16	44	65	97

APPENDIX 15

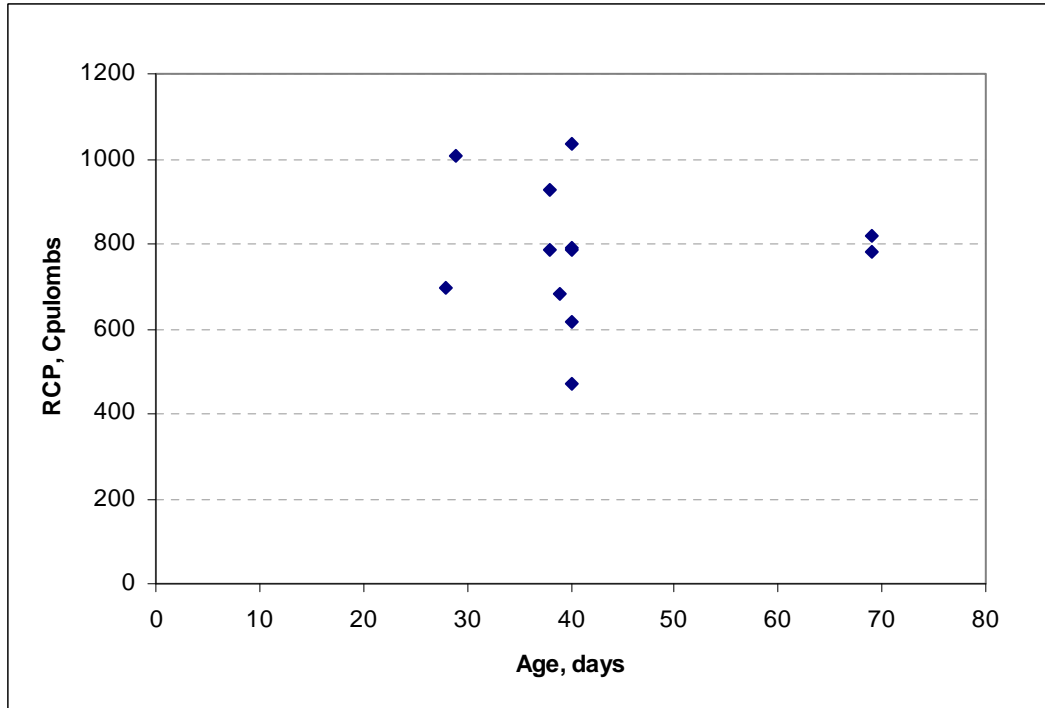


Chart 21 Fly ash concrete RCP results from field sampling and testing by Besix (Grade 40, CM 380kg/m³, fly ash 25% and micro silica 15kg/m³)