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FACTORS INFLUENCING REINFORCED CONCRETE DURABILITY DESIGN IN NEW ZEALAND'S MARINE ENVIRONMENT

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Factors Influencing Reinforced Concrete Durability Design In New Zealand's Marine Environment

By D.H. Chisholm

Synopsis: Changes to the New Zealand concrete design standard incorporate requirements for durability, based on a minimum design life of 50 years for structural elements as required under the New Zealand building code. Many New Zealand cities are near the coastline and concrete quality and reinforcement covers are designed to control chloride induced reinforcing steel corrosion. Four exposure classifications in the standard require increasing protection from chlorides based on increasing exposure to a marine environment. The paper outlines how these exposure classifications were established.

The concrete structures standard specifies minimum concrete strength and reinforcement cover based on the use of normal portland cement concretes for each classification. The enhanced durability performance of some blended cement concretes is recognized along with the role of concrete coatings, and alternative combinations are permitted provided the designer establishes equivalent performance. A BRANZ research program is targetted towards developing an assessment methodology in the laboratory for evaluating the durability performance of blended cement concretes against normal portland cement concretes. The first stage of a laboratory program evaluating the performance of normal portland, slag, silica fume and flyash cement blend concretes is reported. Evaluation methods used included absorption, rapid chloride ion penetration, chloride diffusion and chloride ponding. Further research using site surveys of concrete structures in the near coastal zones is planned.

D.H. Chisholm has been associated with the Cement and Concrete Industry for 18 years. As Construction Engineer for the Cement and Concrete Association of New Zealand, he has written a number of articles, and provided industry training and technical consultancy. He currently manages the Cement and Concrete laboratory and consultancy for BRANZ (Building Research Association of New Zealand) which specialises in concrete durability testing and research.

INTRODUCTION

In 1993, the New Zealand Building Code[1] was published. For the first time the New Zealand construction industry was bound by a performance-based uniform building code across a wide range of building functions - structural performance, durability, thermal characteristics, fire, etc. The durability performance requirement is based on a design life of 50 years for structural building components, apart from special cases where a longer or shorter design life can be justified.

The latest New Zealand Concrete Structures Standard NZS 3101:1995[2] is presented as a performance based standard, and includes a section on design for durability to meet the 50 year Building Code requirement. New Zealand is an island country with four of its five major cities within five kilometres of the coastline. The marine environment poses the most significant threat to reinforced concrete durability, and the latest standard requires an increase in concrete quality and reinforcing steel covers, particularly for structures within 500 metres of the coastline, over the previous requirement. New Zealand has an agricultural and pastoral economy, and little heavy industry, hence industrial pollution does not generally pose a threat to reinforced concrete durability.

This paper outlines the rationale behind the durability requirements of the Concrete Structures Standard and presents results to date of the BRANZ research program on concrete durability, with emphasis on marine chloride penetration of concrete, along with the future direction of that program.

NEW ZEALAND STANDARD DESIGN FOR DURABILITY

The New Zealand Concrete Structures Standard requirements for concrete durability are modelled on the Australian Concrete Structures Standard AS 3600[3]. This will assist in the future harmonization planned for the two standards.

The procedure given in the standard requires the designer to classify the severity of the environment to which the concrete surfaces are exposed. For surfaces of members in above ground exterior environments, there are four exposure classifications of increasing exposure to marine chlorides - Inland (A2), Coastal Perimeter (B1), Coastal Frontage (B2), and Tidal/Splash zones (C). All, except the last classification, are based on the concentration of wind-blown chlorides in the atmosphere. For a particular exposure classification, a minimum concrete quality is defined by specified compressive strength (f'c) and then a minimum cover is required to protect the reinforcement. (Table 1).

The level of protection is based on t_I, the time to initiation of corrosion which is the time taken for chlorides to reach the level of the reinforcement in sufficient concentration for the corrosion protection of the reinforcement to be impaired (after Tuutti[4]). It is realized that this approach is somewhat conservative and simplistic and other factors are involved. (An analysis of a research program carried out by CSIRO Australia, including the influence of bar size and comparison with the AS 3600 requirements, is given in reference[5].)

Many parts of New Zealand are seismically active, and critical components of concrete structures rely on the integrity of confining stirrups to resist earthquake forces. The protection of these stirrups at minimum concrete cover levels is therefore important, and leads to conservative concrete durability design.

Table 1 is based on the use of normal portland cement concretes and a minimum wet curing period of three days for exposure classification A2, and seven days for B1, B2 and C. Because compressive strength can be easily specified and measured, f'c has been adopted as the compliance criterion in most cases. However, it is recognised that compressive strength is at best only an indirect measure of the concrete quality in place from a durability viewpoint, reflecting only the quality of concrete test cylinders after 28 days standard curing. Because the durability of reinforced concrete is dependent primarily on the thickness and quality of the cover concrete, lack of curing on site will impair durability to a greater extent than strength. This highlights the need for in-place testing for final acceptance of construction.

For the most severe exposure classification, C, in the tidal/splash zone, protection to the reinforcing steel is only provided with concretes of low w/c, where the capillary pores are discontinuous. Hence a minimum cement content of 350 kg/m^3, and a maximum water/cement ratio of 0:40 are specified in addition to a minimum concrete strength. The minimum covers have been increased from those recommended in AS 3600 on the basis of research carried out in the United Kingdom by Taywood Engineering Ltd.[6]

NZS 3101 recognizes the enhanced durability performance of some blended cement types. It requires the designer to establish equivalence of performance to normal portland cement concretes, with alternative combinations of concrete quality and reinforcement cover. Some guidelines on appropriate test types are given, however, there is no defined methodology for determining equivalence. Considerable concrete durability research is being carried out worldwide, with various test methods showing a range of comparative performance of blended cement concretes to normal portland cement concretes. The BRANZ research program is designed to evaluate various test methods for both normal and blended cement concretes available in New Zealand, for their ability to predict the durability performance of reinforced concrete structures in a coastal environment.

NZS 3101 also recognises the role of specialist coatings or surface impregnation in reducing chloride ingress. Alternative combinations of concrete quality and cover are allowed provided the overall system can demonstrate equivalent performance to uncoated normal portland cement concretes.

ESTABLISHMENT OF EXPOSURE ZONES

The boundaries between different exposure zones were established from atmospheric corrosivity data based on a long-term survey carried out by BRANZ. For this survey, weight loss due to corrosion is being recorded for steel, galvanized steel and aluminium coupons at 156 sites around New Zealand,[7] [8]. The two-year survey results have been used to produce a map of New Zealand in the Concrete Structures Standard giving the location of the boundary between the A2 and the B1 exposure classification zones. This boundary corresponds to an exposed steel corrosion rate of approximately 150 grams/m^2/year and varies between 1 km and 20 km inland from the coastline depending on whether the prevailing wind is on-shore or off-shore.

The exposed steel mass loss was used to determine a corrosion risk only, but would be expected to be related to chloride deposition rates in coastal regions. In fact, initial BRANZ studies produced an earlier map based on sodium measurements in grass as a predictor of chloride deposition levels. This earlier map correlates well with the latest survey map, but was not as comprehensive as it was based on far fewer sites.

The boundary between the B1 and the B2 zone corresponds to typical exposed steel corrosion rates in excess of 180 grams/m^2/year, which can be considered an 'aggressive' environment. Typically such locations are 100 metres to 500 metres from an open sea situation. The boundary is greatly influenced by localized wind patterns at the site, and specific guidelines are given for the four major coastal urban regions (Table 2) as well as localized maps (Fig. 1). The designer can use discretion in deciding between the B1 and B2 zone. A particular site's exposure may be influenced by topography of the land or the proximity of other buildings, for instance.

BRANZ DURABILITY RESEARCH

The BRANZ research program is a long term program based on a laboratory evaluation of various durability test methods, along with a study of the durability performance of aged reinforced concrete structures located in zones B1 and B2. The field study will in particular measure the presence and effect of chloride ingress, and, where feasible, compare actual performance with that predicted from in-situ and laboratory based durability assessment methods. This paper presents the laboratory program completed to date.

Materials and Mixtures

A series of eight mixtures were made to a batch volume of 75 litres in the laboratory pan mixer using 19 mm and 13 mm crushed greywacke coarse aggregates in a ratio of 3:2, and a natural greywacke river sand. A constant coarse aggregate quantity of 1090 kg/m^3 was used for all mixtures resulting in a sand percentage ranging between 40% and 44% by mass. Details of the cementitious component of the mixtures are given in Table 3 which shows proportions of cement (GP), slag(S), flyash (FA) and silica fume (SF). The target slump for all mixtures was 80 mm, for all the blended cement mixes a superplasticizer was added at the dosage rate given. The slag blends required the highest dosage, followed by silica fume mixtures.

Compressive Strength

Nine 200 x 100Ø mm cylinders were cast for each mixture, and standard cured in a fog room (21°C, 100% RH) for testing at 7, 28 and 91 days. The compressive strength development is given in Figures 2a and 2b.

Durability Sampling

100 mm thick panels, 600 mm deep and 400 mm wide were cast for each mixture, to be sampled for durability assessment. These were cast upright as a wall section and vibrated with a 40 mm internal vibrator. Each panel was wet cured in the fog room for 7 days and then placed in a controlled environment room at 23°C and 50% R.H. Samples were cut from cores taken from the panels at the various test ages. This method of obtaining samples was thought to better represent site practice than had samples simply been obtained from cast cylinders. Three replicate samples taken from the top, middle and bottom of the panel as cast were used for each of the following tests :-

- Water absorption according to BS 1881 Part 122[9] on 75 mm diameter cores taken at 28 days.

- Initial Surface Absorption Testing (ISAT) according to BS 1881 Part 5[9] was carried out at age 42 days and 105 days on positions located in the top, middle and bottom regions of the formed surfaces of the panel. The panel was preconditioned in the laboratory by being left to dry for a minimum of 48 hours after wet coring.

- Rapid chloride ion penetration according to ASTM C1202[10] on 100 diameter mm cores taken at 28 days and 91 days.

Chloride diffusion testing using the Taywood diffusion cell. This is described in Section 4.7.3 of reference[12] . A 15 mm thick slice of concrete is placed between two reservoirs each containing sodium hydroxide. One reservoir is filled with 5M NaCl solution and the increase in chloride content with time of the other reservoir is measured to determine the flow rate due to concentration difference. The chloride diffusion rate is determined by applying Fick's first law once a steady flow rate is achieved.

The 15 mm slice was taken from the outer faces of a 100 mm diameter core taken at 28 days. Samples were arranged so that chloride diffusion was from the outside formed surface towards the cut surface.

In addition a single 100 mm x 100 mm x 600 mm long prism was cast for each mix for immersion in chloride solution and determination of chloride ingress. Prisms were wet cured for 7 days, then dried in a controlled environment room (23°C 50% RH). At 28 days, 200 mm was cut off the prism and used as a control, and the remaining 400 mm long prism was placed in a 3M Na C1 solution, with the top face as cast covered to a depth of 10 mm.

After an immersion period of 91 days, the prism was removed for analysis. The extraction of the concrete samples from the prism was initially based on the method used in reference [11]. A 150 mm long section was cut off the prism and the remaining 250 mm long prism was placed back in the chloride solution. Powder samples for chloride analysis were obtained by drilling 8-mm diameter holes perpendicular to the freshly-cut surface. The holes were drilled at distances of 10, 25, 50, 75, 90 mm from the side of the prism as cast as shown in Figure 3. Three holes were drilled at each selected distance grouped at the mid depth of the prism and combined for analysis using X-ray flourescent spectrophotometry. The holes were drilled approximately 25 mm deep with powder from the first 1 mm (approximately) being discarded.

The remaining prism was removed after a total immersion period of 220 days. It was then cut in half and 25-mm deep sawcuts were made perpendicular to the freshly cut surface, so as to produce 10-mm thick slices centred at distances of 10, 25, 50, 75, 90 mm from the side of the prism as previously. Each slice was then trimmed to a height of 25-mm representing the middepth of the prism. The 25mm square samples were then ground for chloride analysis.

Durability Results and Discussion

The 30-minute water absorption results (BS 1881 Part 122) are given in Table 4. All results are well below 3% which can be classed as low absorption concrete[12]. The low range of results (0.4%) suggests that the test is not sensitive enough to measure performance differences in high-performance concretes. The lowest absorptions were measured for the two silica fume blend concretes.

The ISAT results (BS 1881 Part 5) for the 10-minute, 30-minute and 60-minute readings are given in Table 4. All results correspond to a classification of low absorption concrete[12]. Whilst the ranking of results across the range of mixes for the 10-minute reading at age 42 days and 105 days is consistent, the results for the later test age were higher, which was unexpected. It is unlikely that extended curing was possible in the dry atmosphere (50% R.H.), and instead, the further drying out of the concrete has resulted in a higher ISAT reading at the later test age.

The ISAT test is sensitive to concrete moisture levels, and laboratory testing of oven dried samples, whilst giving higher readings, results in lower within-test variations. Applying a vacuum to the ISAT apparatus prior to site testing in order to achieve a uniform preconditioning has been proposed,[13] to reduce test variability due to concrete moisture content.

The ranking of the concrete types from the ISAT readings is questionable given that there was no significant preconditioning and the concrete moisture content differences could affect the relative readings. It is considered that the preconditioning for 48 hours of drying (50% R.H.), is inadequate for testing of high-performance concretes. The dry conditions after the initial 7 day wet curing is likely to have more effect on the strength and general durability development of the blended cement concretes than the normal portland cement concretes owing to the slower hydration rate.

The rapid chloride test results (ASTM C1202) and chloride diffusion test results are given in Table 4. ASTM C1202 is a standard test method giving an electrical indication of concrete's ability to resist chloride ion penetration. It is widely acknowledged that it is not a measure of chloride diffusion, although it can be used to rank concretes with a similar binder type for chloride penetrability.

Figure 4 shows the Taywood chloride diffusion results in m^2/s plotted against rapid chloride test values in coulombs. There appears to be no clear relationship between the two measures, and results are grouped according to their binder type. Whilst the slag and silica fume blend concrete had both low rapid chloride and chloride diffusion values compared with the GP cement concretes, the fly ash blend concretes had chloride diffusion values up to 5 times lower than the GP concrete but with similar rapid chloride ion values. This confirms that rapid chloride test values cannot be used to rank chloride ion penetrability across cement blend types.

Comparing both the rapid chloride test and Taywood chloride diffusion results for the two silica fume concretes, LD5a and 5b, the values for the higher cementitious content mix, LD 5b, were unexpectedly higher. This may be due to the fact that LD 5b used a densified silica fume powder. Although the laboratory pan mixer has a more vigorous action than a typical ready-mixed drum mixer, the mixing action may not have been sufficient to break up and fully disperse the silica fume powder. The 91 day compressive strength of LD 5b is also less than LD 5a.

The reduction in the rapid chloride test value after 91 days of curing compared with 28 days of curing is consistent with other research.[14]

Based on the Taywood chloride diffusion values obtained, the 75% slag blend concrete performed the best, followed by silica fume, flyash and then GP cement concrete. The relative penetrability difference between the different cement blends may not be as high as the relative diffusion coefficients however. A steady state flow rate was reached for mix LD 1b after 130 days compared with 330 days for mix MD4. The additional test time would lower the apparent diffusion coefficient based on the observed reduction in diffusion with time[6].

The chloride profiles resulting from the immersion tests were calculated as chloride content as a percentage of cement versus depth of penetration for 10, 25 and 50 mm. The chloride content of samples taken at side distances of 25 mm and 75 mm, and of 10 mm and 90 mm were averaged. Values were adjusted for the baseline level of chloride determined from the control samples which were not immersed. The results are given in Figures 5a - 5d.

No clear pattern emerged from the results, and it is considered that an oversight in the test procedure affected the results. Only one prism was made for each concrete type and the relative size of the samples taken for chloride analysis is such that the predominance of coarse aggregate in any one sample would significantly affect the result. The sampling was restricted to a 30 mm band at the mid depth of the prism to ensure that the chloride present resulted only from unidirectional flow from the sides and not from the top and bottom of the prism.

It is considered that the influence of the coarse aggregate could be reduced by epoxy coating the top and bottom faces of the prism ensuring unidirectional chloride flow and allowing a wider band to be used for chloride analysis. In addition, the aggregate size could be reduced or the depth and number of prisms increased. Other researchers[15] have removed the aggregate by breaking each slice of concrete in order to recover only the material from the mortar fraction for chloride analysis. This aspect of the work is to be repeated.

CONCLUSIONS

In the first stage of a BRANZ research program evaluating the potential durability performance of concrete in a marine environment, four concrete types made using GP cement, 75% slag, 10% silica fume, and 25% flyash blends based on cement replacement were evaluated in the laboratory.

1. - Comparing compressive strength gain to 91 days, only the slag blend gave strengths significantly below the GP control.

2. - Absorption testing according to BS 1881 Part 122 is not sensitive enough to measure potential durability performance differences in high- performance concretes.

3. - ISAT testing according to BS 1881 Part 5 requires preconditioning of concrete to a uniform moisture content to reduce test variation.

4. - Chloride diffusion testing (Taywood cell) showed significant improvement for all blended cement concretes compared with GP cement concretes. The slag blend has the lowest diffusion values followed by the silica fume and flyash blends. Significant chloride durability improvements are available through the use of blended cement concretes. These have application in particular in the splash/tidal zone C of NZS 3101:1995.

5. - The rapid chloride test (ASTM C1202) does not correlate well with chloride diffusion. It can be only used to evaluate relative durability performance within a particular cement blend type.

6. - Blended cement concretes using densified silica fume may require a specialized mixing regime to break up and disperse the silica fume to ensure performance improvement.

7. - In sampling concrete for chloride analysis and development of chloride profiles, sampling must avoid a predominance of coarse aggregate in any one sample which significantly affects the result.

FUTURE RESEARCH

Further laboratory testing will include immersion tests with a revised sampling regime. Future ISAT testing will be carried out on preconditioned samples, either oven dried in the laboratory or vacuum dewatered on site. A new technique[16] for measuring the air permeability of near surface concrete by application of a vacuum shall be evaluated.

A natural pozzolan rich in silica now available in New Zealand will be included in future research. Research being carried out by Works Central Laboratories will evaluate time to corrosion of reinforced concrete test samples made based on the concrete mixes used in the BRANZ program. A survey of concrete structures in the B1 and B2 coastal zones is to link in with an extended laboratory test program.

The BRANZ research program is targeted towards developing an assessment methodology in the laboratory for evaluating the durability performance of blended cement concretes against GP cement concretes to fulfil the requirements for durability design in the NZ Concrete Structures Standard.

ACKNOWLEDGEMENT

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Table 1. Minimum required cover for various exposure classifications (from NZS 3101:1995)

Exposure Classification	Specified compressive strength f'_c (MPa)							
	17.5	20	25	30	40	50	60	70
	Minimum required cover to steel reinforcement (mm)							
A2	50	40	35	30	25	25	20	20
B1	65	50	40	35	30	30	25	25
B2	-	-	50	45	40	35	30	30
C	-	-	-	-	-	70*	65*	60*

* *Also normal portland cement content of not less than 350 kg/m^3 and water cement ratio not exceeding 0.40 are required.*

Table 2. Definition of coastal frontage zone (B2) for Main New Zealand urban regions

General	Within 100 m of the high tide mark. Or, within 500 m of the high tide mark onshore in the direction of a prevailing or other common wind.
Auckland region	Within 100 m of the high tide mark. Or, within 500 m of the high tide mark to the Southwest.
Wellington region	Within 100 m of the high tide mark. Or, within 500 m of the high tide mark to the North, South, or Northwest.
Christchurch region	Within 100 m of the high tide mark. Or, within 500 m of the high tide mark to the Northwest, Northeast, or Southwest.
Dunedin region	Within 100 m of the high tide mark. Or, within 500 m of the high tide mark to the Northeast or Southwest.

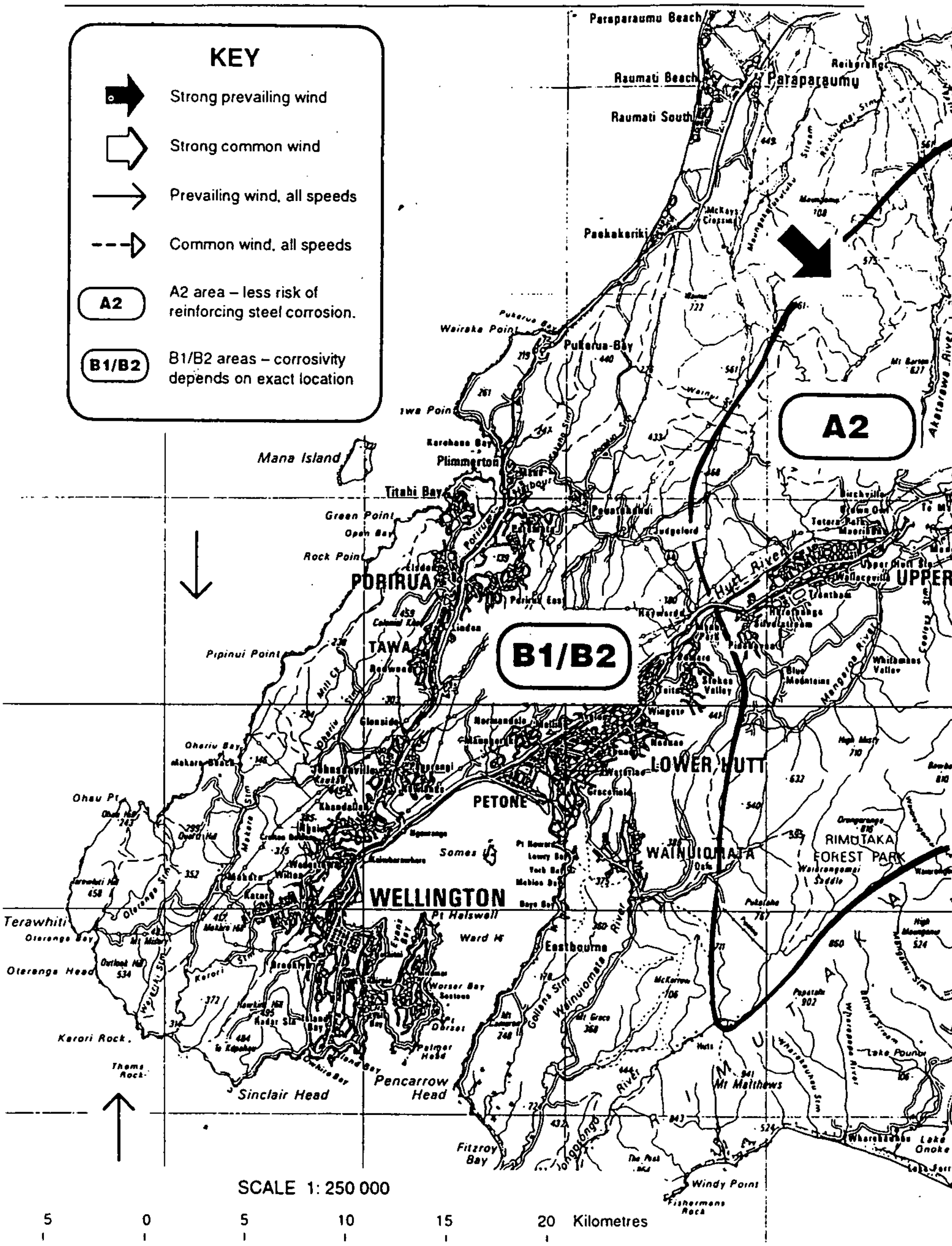
Table 3. Concrete mix details by Cementitious Material Type

Mix No.	Cementitious Type	Cementitious Material Content	Proportion % Cement Replacement				Water / Cementitious	SP Dosage % on Cement
			GP	S	FA	SF		
LD 1a	Type GP Cement (Normal Portland Cement)	325	100	-	-	-	0.47	-
LD 1b	Type GP Cement (Normal Portland Cement)	400	100	-	-	-	0.40	-
LD 2a	75% Slag Blended Cement	325	25	75	-	-	0.47	0.6
MD 4	75% Slag Blended Cement	400	25	75	-	-	0.40	0.8
LD 5a	Cement with Silica Fume Slurry	325	90	-	-	10	0.47	0.46
LD 5b	Cement with Densified Silica Fume	400	90	-	-	10	0.40	0.53
LD 6a	Cement with Australian Flyash Class F	325	75	-	25	-	0.48	0.23
LD 6b	Cement with NZ Flyash Class C	400	75	-	25	-	0.39	0.17

SP = Superplasticizer

Table 4. Absorption, rapid chloride test and chloride diffusion results

Mix No.		LD 1a	LD 1b	LD 2a	MD 4	LD 5a	LD 5b	LD 6a	LD 6b
Cementitious Content (kg/m^3)		325	400	325	400	325	400	325	400
Cementitious Type		GP Cement	GP Cement	Slag	Slag	Silica Fume	Silica Fume	Flyash	Flyash
BS 1881 Absorption (%) 28 Day		2.10%	2.20%	2.17%	2.03%	1.88%	1.83%	2.23%	2.00%
ISAT ($ml/m^2/s$)	10 min	0.072	0.14	0.124		0.196	0.125	0.188	0.104
At 42 Days	30 min	0.031	0.054	0.061		0.092	0.054	0.077	0.049
	60 min	0.025	0.031	0.036		0.063	0.029	0.054	0.034
ISAT ($ml/m^2/s$)	10 min	0.12	0.184	0.186		0.21	0.179	0.285	0.13
At 105 Days	30 min	0.057	0.083	0.076		0.064	0.078	0.122	0.082
	60 min	0.032	0.034	0.044		0.034	0.042	0.08	0.052
Rapid Chloride Test	28 day	4174	3415	792	1026	648	1196	3837	4006
(Coulombs)	91 day	3804	3074	544		526	959	3181	2937
Chloride Diffusion (m^2/s)	28 Day	2.40 E-13	1.90 E-13	8.30 E-15	5.80 E-15	2.60 E-14	6.40 E-14	8.40 E-14	3.80 E-14


KEY
Strong prevailing wind
Strong common wind
Prevailing wind, all speeds
Common wind, all speeds
A2
A2 area – less risk of reinforcing steel corrosion.
B1/B2
B1/B2 areas – corrosivity depends on exact location
A2
B1/B2
Paraparaumu Beach
Raumati Beach
Paraparaumu
Raumati South
Paekakariki
Pukerua Bay
Mana Island
Plimmerton
Titahi Bay
PORIRUA
TAWA
LOWER HUTT
UPPER
PETONE
WAINUIOMATA
WELLINGTON
RIMUTAKA FOREST PARK
Eastbourne
Sinclair Head
Pencarrow Head
Fitzroy Bay
Windy Point
Mt Matthews
Terawhiti
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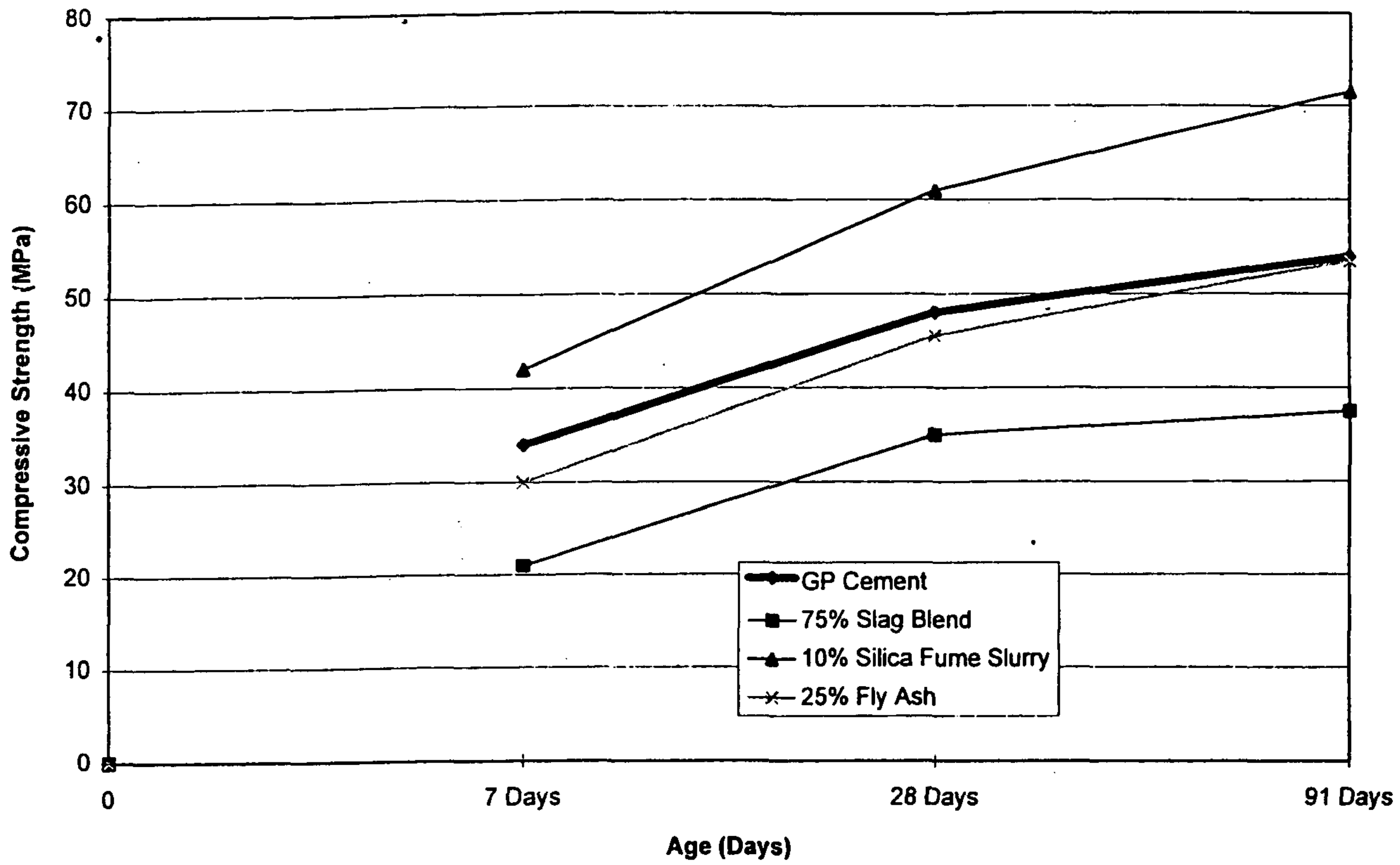


Fig. 2a—Compressive strength development for 325 kg cementitious mixes

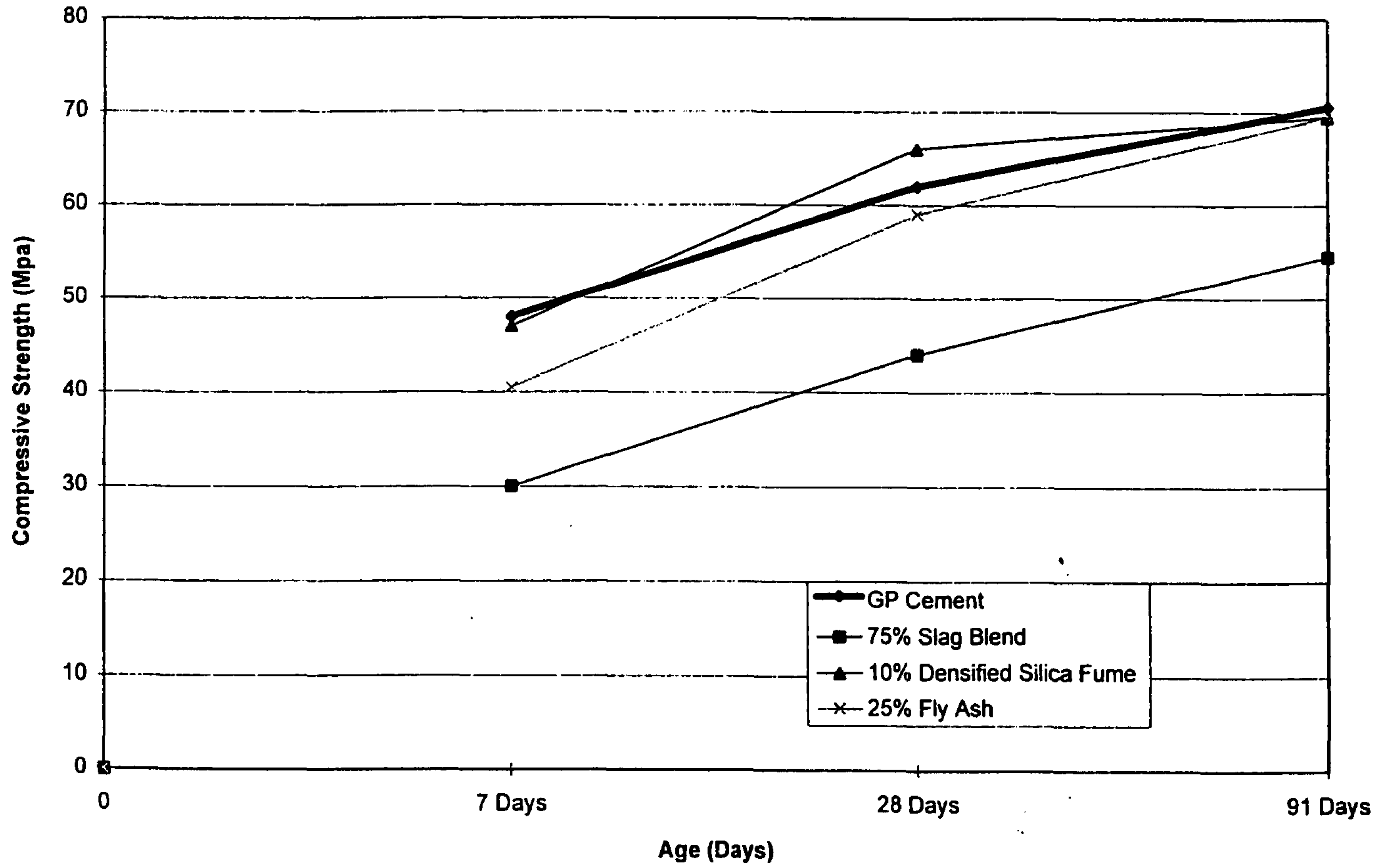


Fig. 2b—Compressive strength development for 440 kg cementitious mixes

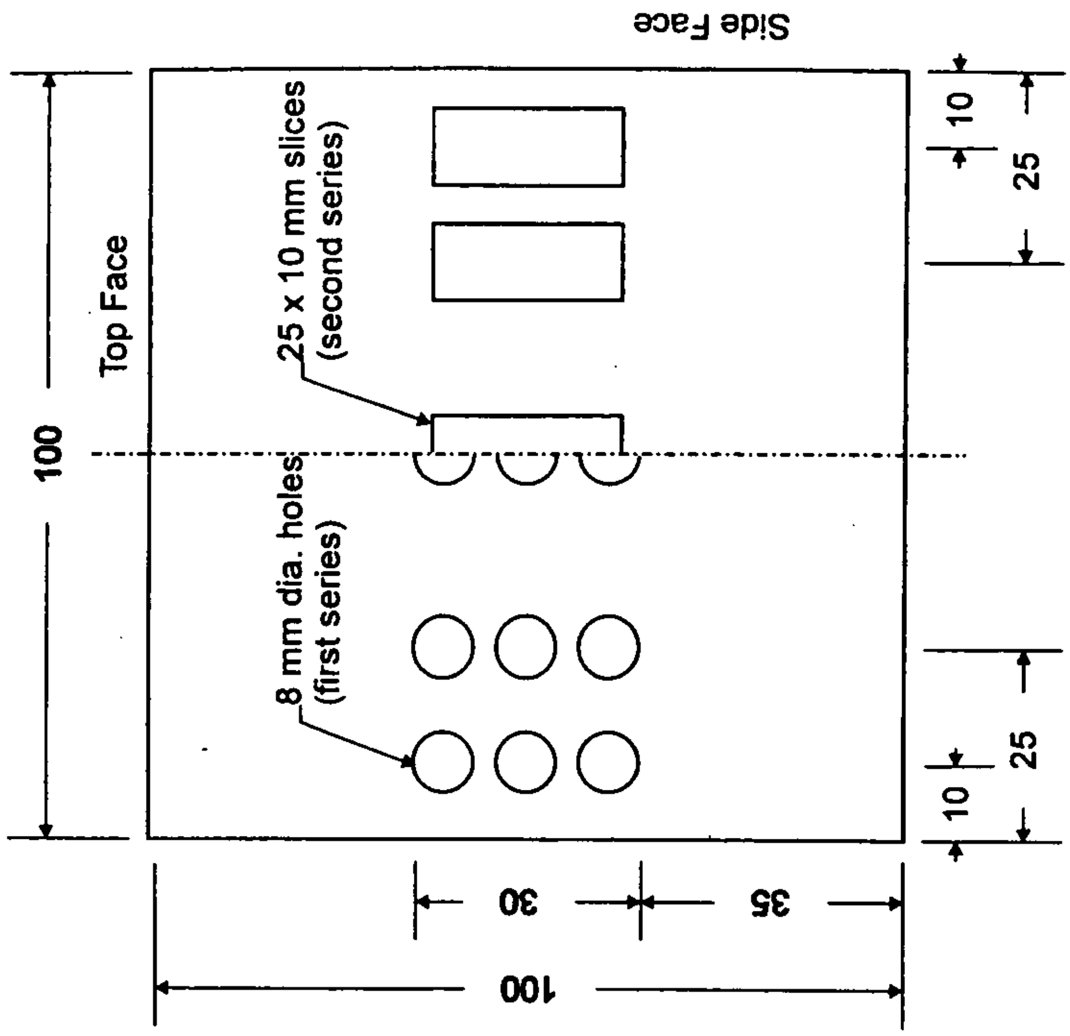


Fig. 3—Location of concrete samples for chloride analysis (immersion test)

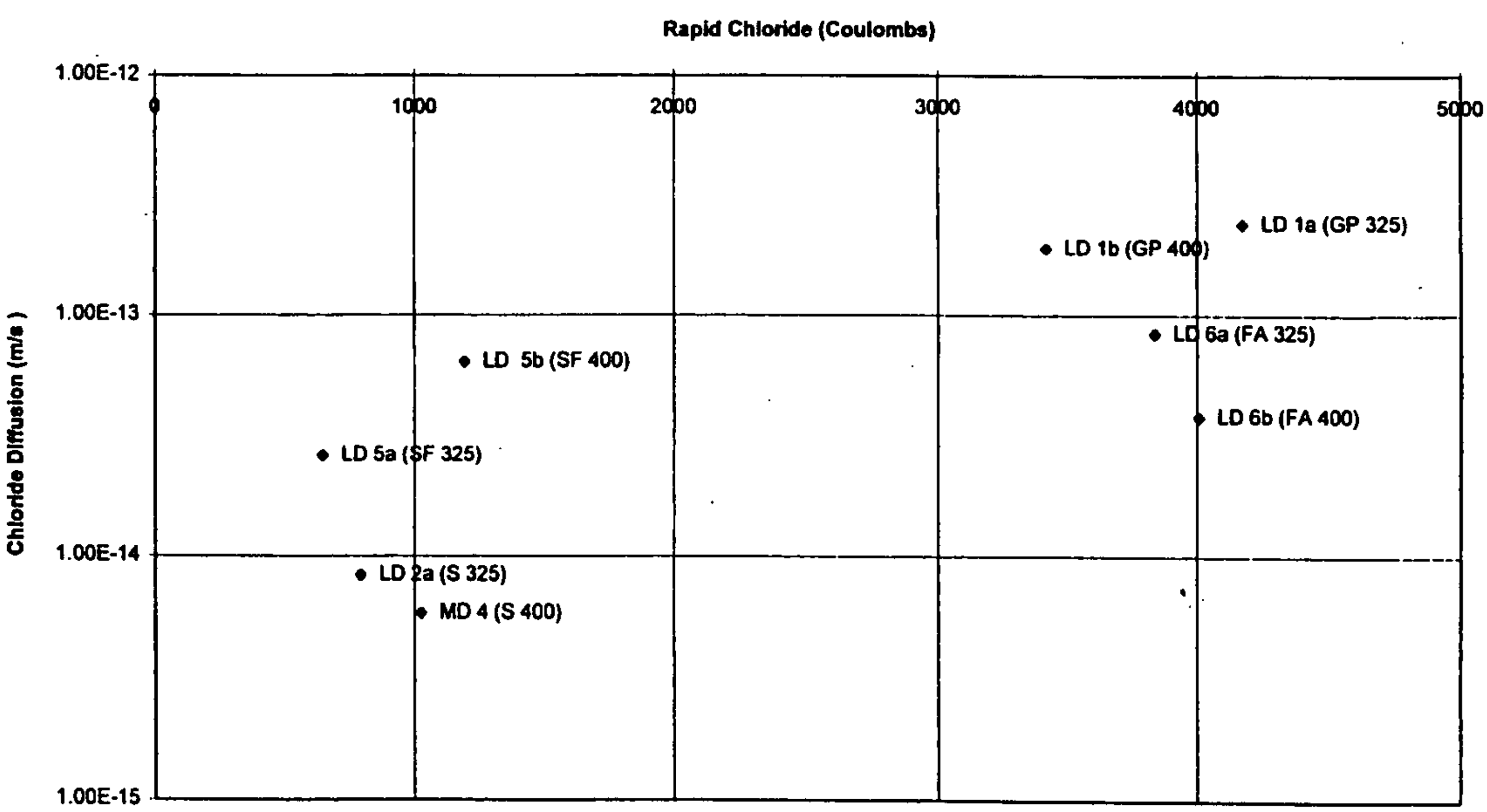


Fig. 4—Chloride diffusion verses rapid chloride test results

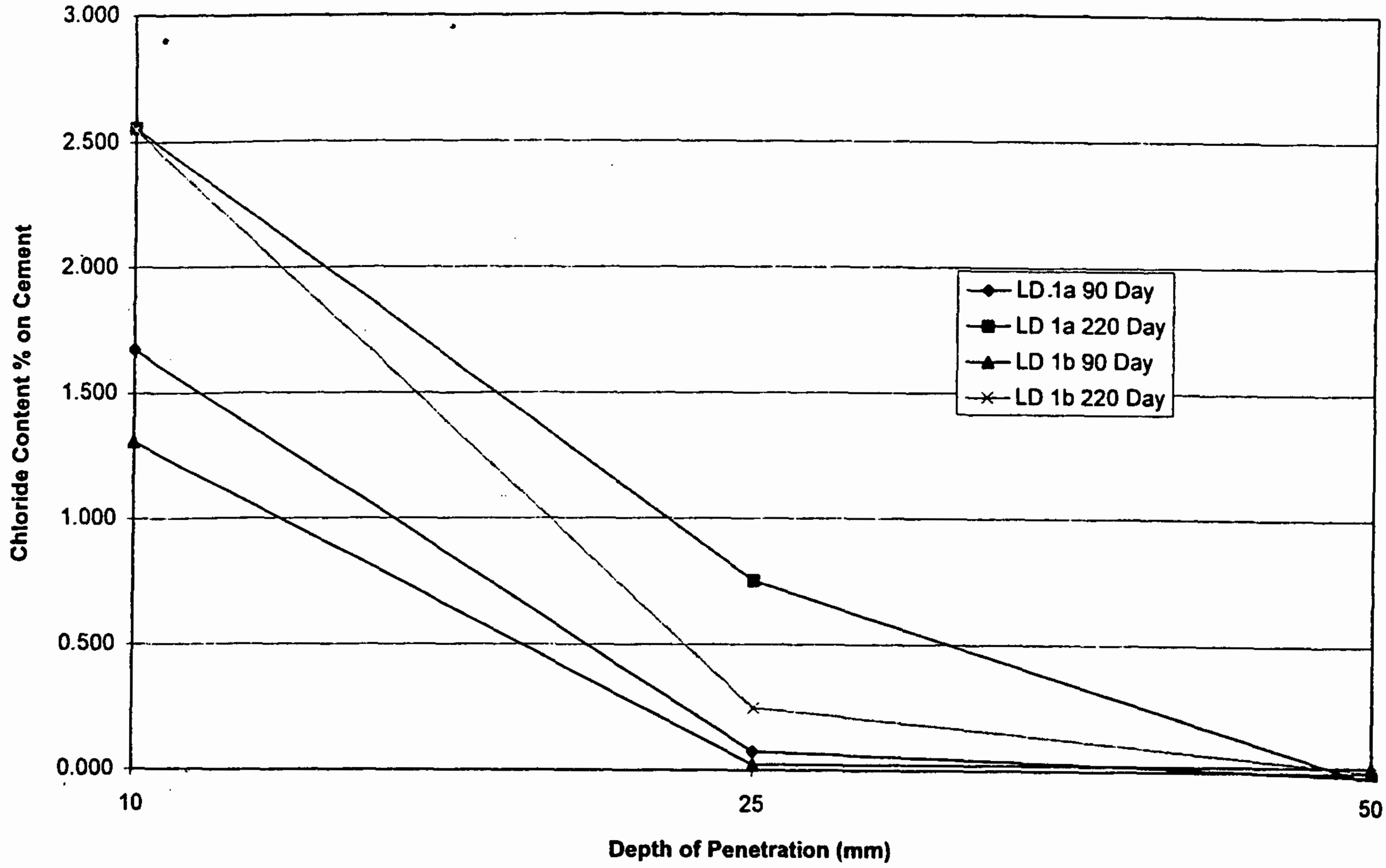
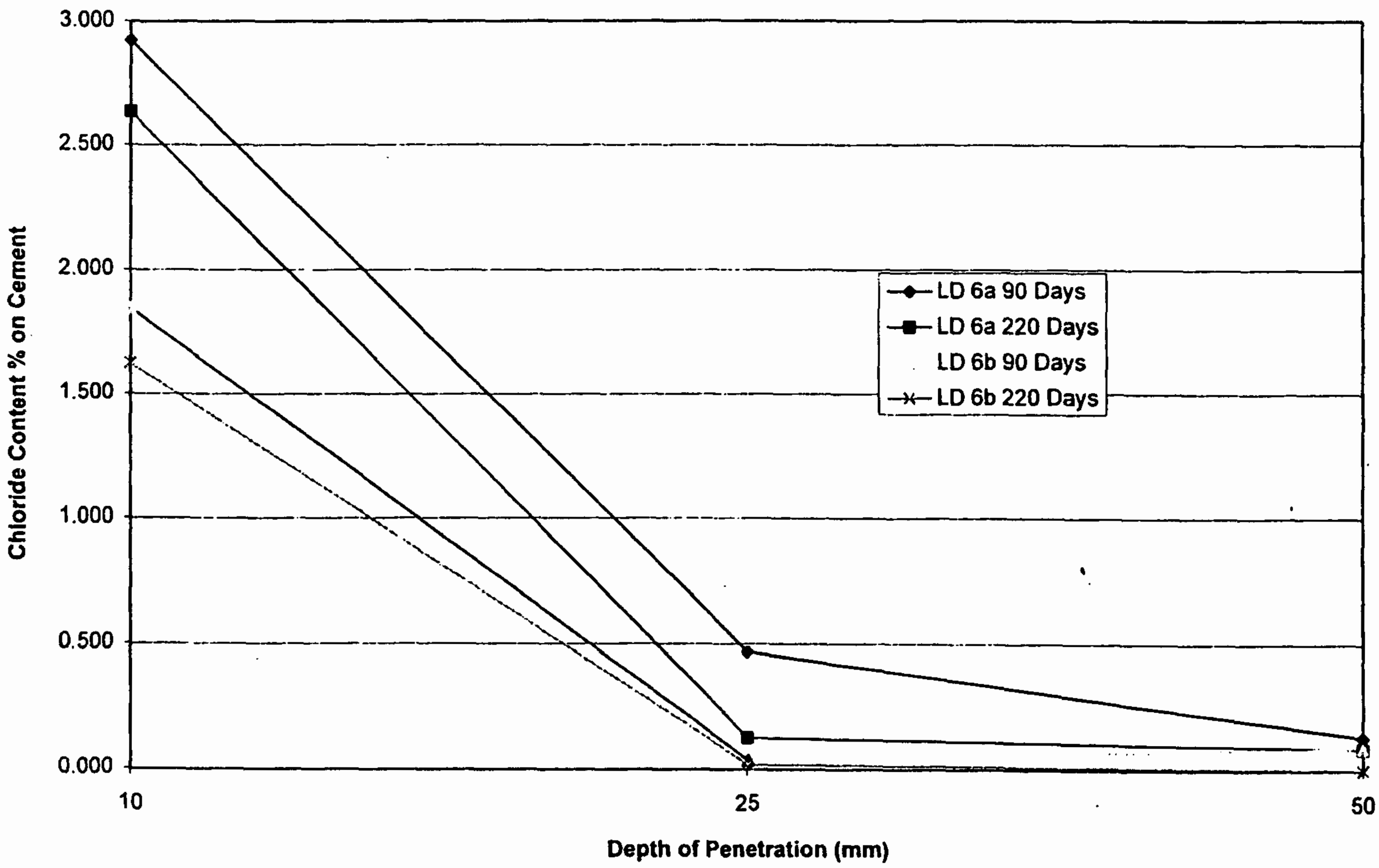
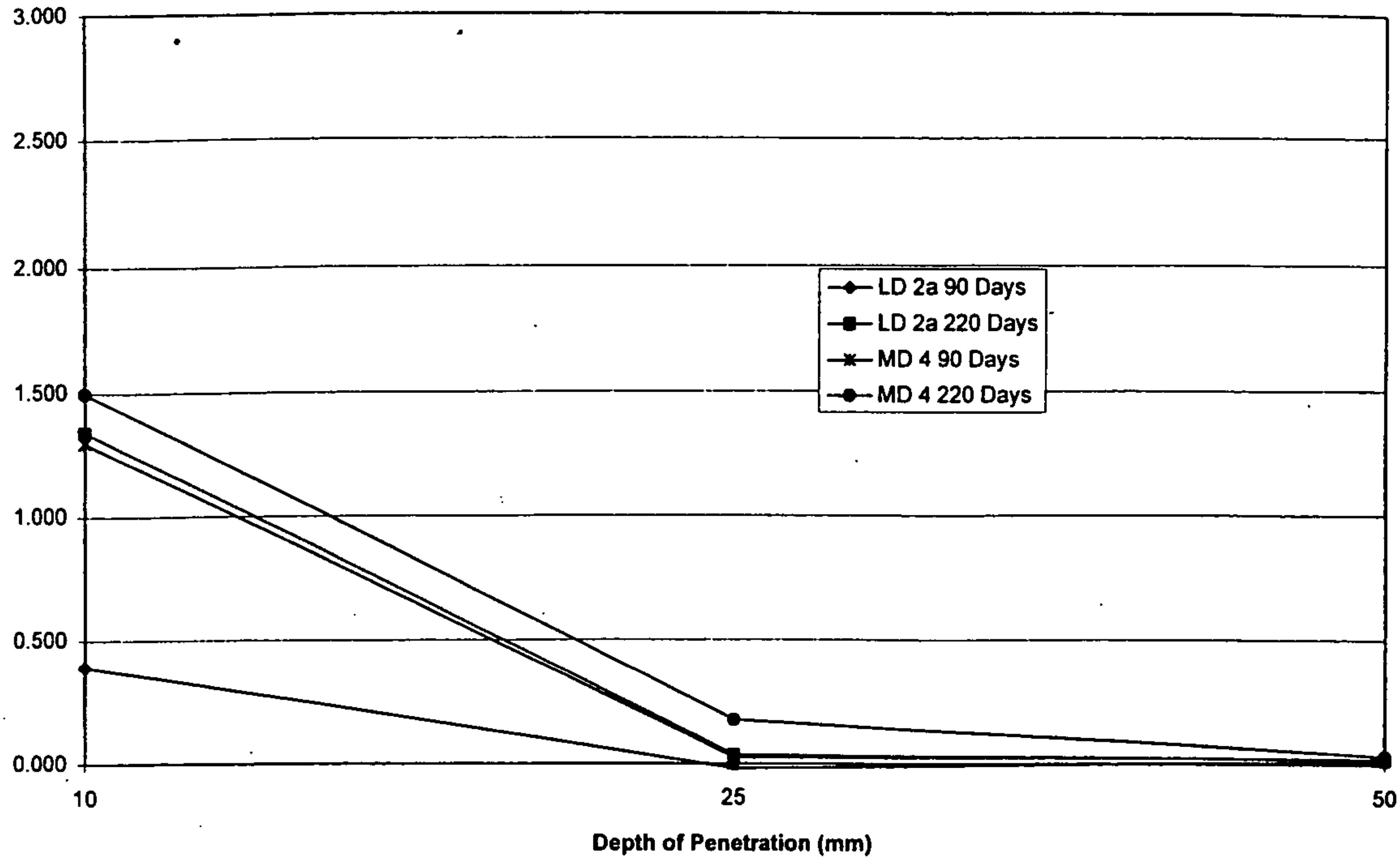


Fig. 5—Chloride profiles for immersion test

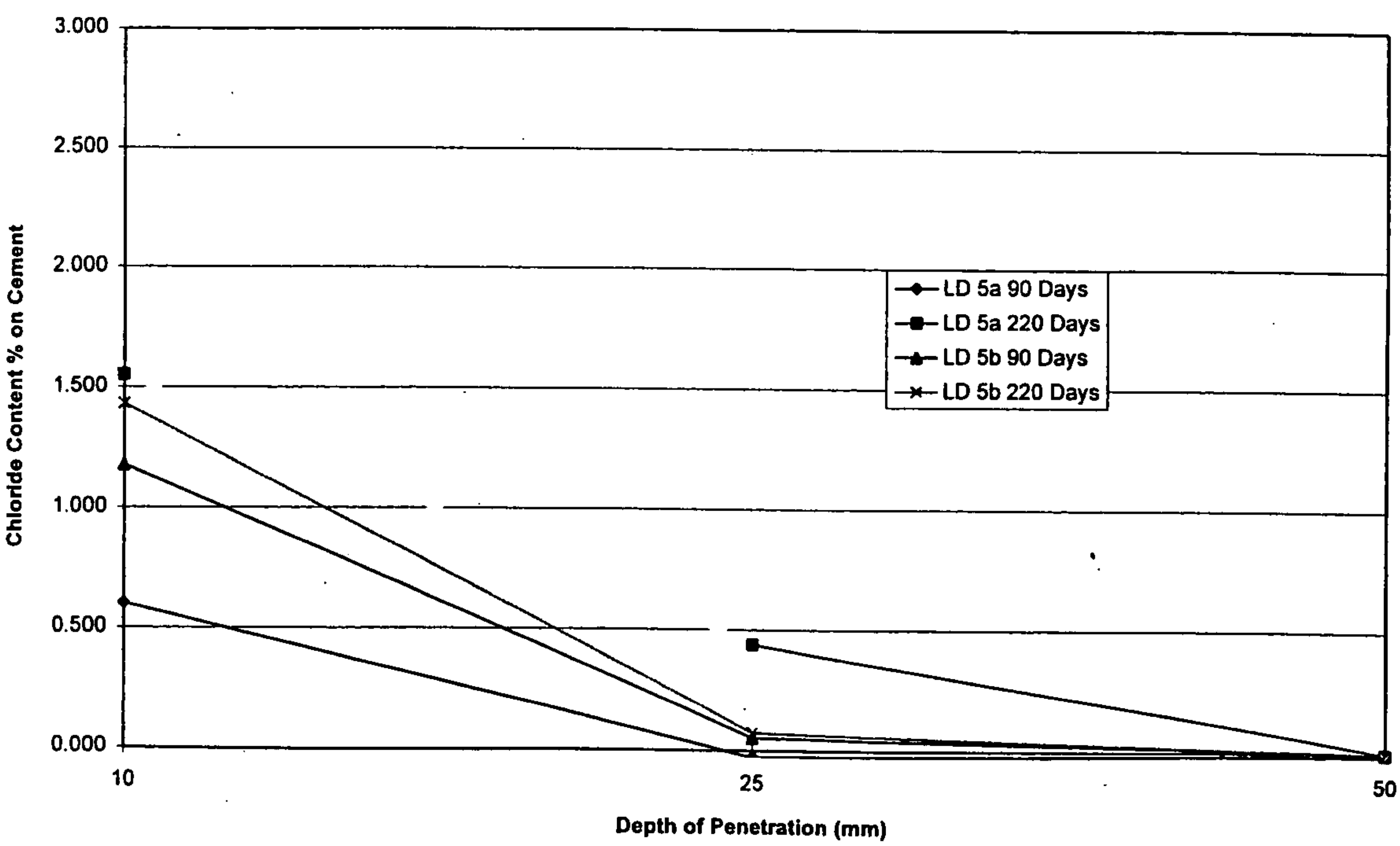
(a) GP cement mixes



(b) fly ash mixes



(c) slag mixes



(d) silica fume mixes

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