Modelling the Service Life of Structures with Cast-in-Place Concrete vs. Wet-Mix Shotcrete

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While shotcrete is increasingly being used as a construction and repair method for many structural elements, one question is frequently asked regarding the use of shotcrete vs. cast-in-place concrete: Do they achieve similar service life?

Two different scenarios were studied and modelled for 9 different mixtures, including cast-in-place concrete and wet-mix shotcrete, with and without accelerators. Modelled results show that shotcrete can achieve similar or better service life in comparison to cast-in-place concrete.

WHAT IS SHOTCRETE?

> ***Shotcreting:*** *The process of pneumatically conveying concrete materials at high velocity to a receiving surface to achieve compaction.*

First developed by Carl Akeley in 1907, shotcrete has been used for a wide variety of applications, including structural shotcrete, seismic retrofit, architectural shotcrete, ground support for tunnels and mines, canal lining, slope stabilization, pools and infrastructure rehabilitation. It has experienced over a century of technological advancements[2][3] in the years since, and because of the efficiencies and economies they can bring to a project, structural shotcrete applications are increasingly being used in structures all around the world.

More and more civil concrete structure constructors are realizing the benefits of using shotcrete in lieu of cast-in-place concrete, primarily due to the reduction or elimination of formwork and the consequent reductions in materials and labour costs. In addition, the shotcrete process is versatile and can be effectively adapted to many challenging construction requirements, such as curvilinear structures like domes, skateboard parks, and luge tracks.

Sophisticated concrete structures with complicated reinforcement details are now routinely being constructed with shotcrete. This can be seen in underground structures in the New York and the Toronto Metro system where thick, heavily reinforced structural walls and other elements are being constructed using shotcrete. Shotcrete is now included in the ACI 318-19 Building Code Requirements for Structural Concrete, and future trends show shotcrete being used for more of these types of structures[4].

Shotcrete technology involves special mixture designs, application equipment, and shotcreter application procedures. The quality of the final product is dependent on both materials and processes, i.e., the wet-mix and dry-mix shotcrete processes.

- The wet-mix shotcrete process is similar to pumped ready-mix concrete, except that compressed air is added at the nozzle at the end of the pump hose to convey the material to the receiving surface at a high impacting velocity.
- The dry-mix shotcrete process conveys the material down the hose with compressed air and requires water to be added at the nozzle, therefore requiring the shotcreter to control the water content of the mixture.

With the increasing use of shotcrete, questions have been raised about its long-term performance and durability. In particular, how does the durability of shotcrete compare to that of cast-in-place concrete?

DURABILITY OF SHOTCRETE VS. CAST-IN-PLACE CONCRETE

This study examines the service life of cast-in-place concretes compared to wet-mix shotcretes with similar water-cementitious materials ratios (w/cm). Relatively little has been published about the service life of shotcrete. Information on this topic is important, since shotcrete is increasingly being used in a wide variety of new concrete construction and repair applications. Recent research results on transport properties of concrete and shotcrete has demonstrated that properly constructed shotcrete structures can provide equal or better transport properties than conventional cast-in-place concrete[1]. The transport properties evaluated included:

- **Absorption:** Liquid uptake in a porous medium
- **Diffusion:** Liquid, gas, or ion movement under a concentration gradient
- **Permeability:** Resistance to flow of a liquid under a pressure gradient

- **Sorptivity:** Absorption of a liquid by capillarity
- **Wicking:** Capillary transport through a porous medium to a drying surface

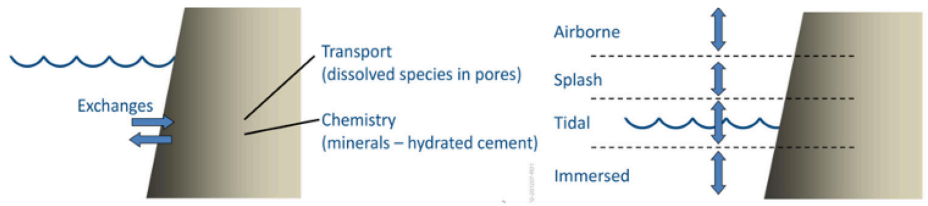

Fig. 1-a) Exchanges of chemical species through the transport process; 1-b) Exposure conditions for marine structures

Using the test results from the previous transport properties study[1], the service life of shotcrete structures was modelled using the STADIUM® model. This model inputs the transport properties for various ionic species generated in a reliable testing environment. STADIUM® is based on the most recent developments in ionic transport modelling and numerical solutions. Service life is calculated based on a finite element model, taking into account nonlinear activity effects, that models the ingress of chloride and other ionic species under different types of environmental conditions (temperature, moisture, chloride ion exposure, etc.).

These transport properties data were input into the STADIUM® modelling program to model the service life of two different shotcrete structures with different exposure conditions.

EXPERIMENTAL PROGRAM

A plain portland cement concrete, fly ash modified concrete, and silica fume modified concrete were cast and tested. In addition, a plain portland cement shotcrete, fly ash modified shotcrete, and silica fume modified shotcrete were shot and tested. The shotcrete tests were also completed on mixtures with rapid-set accelerator added at the nozzle. The cast concrete and wet-mix shotcrete mixtures designs used are provided in Table 1.

Test results indicate that the wet-mix shotcrete exhibits low porosity, low permeability, and reduced coefficients of diffusion[1]. Test results for ASTM C642 Boiled Absorption and Volume of Permeable Voids, ASTM C1792 Drying test, and the ionic migration tests to US Navy Spec UFGS 03 31 29-3[1] were input into the STADIUM® model for service life prediction.

MODELLING PROGRAM

The STADIUM® modelling program requires input of:

- Mixture design and chemical composition of the cementitious materials
- Test results for volume of permeable voids
- Permeability based on a drying test
- Coefficient of diffusion from an ionic migration test.

To initiate a process of ionic migration, details regarding the structural component design, location of the structure, and exposure conditions are required.

STADIUM® models the transport of chemical species in cementitious materials resulting from exchanges at the material-environment interface. For example, Fig. 1a and 1b show the chemical species exchange between the environment and structure for exposure conditions in a marine structure.

Mix. No.	Mix Description	Placement Method	Mix I.D.	As-Batched Mixture Proportions for 1.0 m3										
				Cement (Type GU) (kg)	Fly Ash (kg)	Silica Fume (kg)	Coarse Aggregate (10-5 mm, SSD) (kg)	Fine Aggregate, SSD (kg)	Water (L)	High Range Water Reducing Admixture (L)	Total Mass (kg)	w/cm ratio	Air content, % (As batched)	Air content, % (as-shot)
A1	Portland Cement	Cast Concrete	C-Cast	415	0	0	1027	691	168	0	2329	0.40	5.50%	Not Applicable
A3	Portland Cement	Shot Wet-Mix	C-Wet-Mix-Shot	445	0	0	425	1273	179	0.533	2322	0.40	4.50%	3.20%
A4	Portland Cement	Shot Wet-Mix 5% Accelerator	C-Wet-Mix-Shot-5%	443	0	0	423	1267	179	0.530	2313	0.40	5.90%	3.60%
B1	Fly Ash Modified	Cast Concrete	FA-Cast	334	79	0	1023	688	166	0	2319	0.40	5.30%	Not Applicable
B3	Fly Ash Modified	Shot Wet-Mix	FA-Wet-Mix-Shot	351	86	0	418	1252	176	0	2284	0.40	5.40%	3.50%
B4	Fly Ash Modified	Shot Wet-Mix 5% Accelerator	FA-Wet-Mix-Shot-5%	349	86	0	416	1246	176	0.633	2274	0.40	5.60%	3.90%
C1	Silica Fume Modified	Cast Concrete	SF-Cast	379	0	34	1005	676	166	0.585	2263	0.40	7.20%	Not Applicable
C3	Silica Fume Modified	Shot Wet-Mix	SF-Wet-Mix-Shot	404	0	39	422	1265	178	1.285	2310	0.40	5.10%	3.40%
C4	Silica Fume Modified	Shot Wet-Mix 5% Accelerator	SF-Wet-Mix-Shot-5%	400	0	38	418	1253	177	2.036	2287	0.40	6.60%	4.00%

Table 1: Mixture designs for cast concrete and wet-mix shotcretes

The modelling was conducted to conform with requirements for exposure conditions in ACI, CSA and AASHTO codes and standards. STADIUM® models different types of structures, including bridges, marine structures and parking structures. After applicable structures and exposure conditions were selected, different concrete mixtures were input to compare the chloride initiation, penetration, and migration over time. Parameters obtained from the testing and calculations were entered into the STADIUM® model, including:

Mixture Design: Binder (cement + supplementary cementing materials) Content, Water:Binder ratio, Total Aggregates, Cement Chemistry, Boiled Absorption and Volume of Permeable Voids, Porosity, Coefficient of Diffusion, Age of First Exposure and Age of Laboratory Testing.

The modelling considered requirements for durability in the ACI, CSA and AASHTO codes and standards.

MODELLING METHODOLOGY

The service life was modelled for ages ranging up to 100 years.

Two different structures were selected for modelling. Structures were modelled with each representing a particular structure in a specific location with the most severe environmental exposure condition as detailed below:

- **Bridge Structure in Chicago, IL:** In this structure, exposure to de-icing salt was selected as the corrosion inducing mechanism.
- **Caisson Structure in Tampa, FL:** In this structure, seawater exposure in the tidal zone was selected as this is the most severe condition that will cause corrosion.

All 9 mixtures were modelled for each structure, therefore, a total of 9 mixtures x 2 structures = 18 scenarios were modelled. Results were analyzed and compared for the reference mixture, cementitious materials, and addition of alkali-free rapid-set accelerator, if used.

Uncoated black steel was selected as the reinforcement as it's the most commonly used type of reinforcing steel and is made of unfinished tempered steel which is susceptible to corrosion. No corrosion inhibiting admixture, coating or any other type of steel, including MMFX and stainless steel, were selected in this modelling. This paper compares the effect of chloride ion penetration and corrosion initiation in black steel over time for structures constructed or repaired with shotcrete and cast-in-place concrete for the selected structures.

The Federal Highway Administration[2] suggests a chloride threshold value of 0.30% of the cement by mass of binder, a conservative value, since it is in the lower range of values reported in the literature. Based on this FHWA value for a concrete having a cement content around 690 lb/yd³ (410 kg/m³) and a bulk dry density around 141 lb/ft³ (2,250 kg/m³), the chloride threshold is around 0.05% by mass of concrete (500 ppm). In STADIUM®, the user can modify the threshold value using the Preference tab[3].

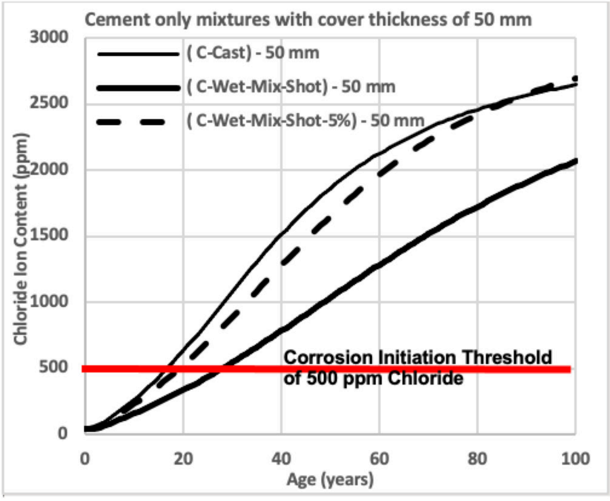

Fig. 2a) Chicago Bridge Structure chloride ion content development with time for cement only mixtures with cover thickness of 50 mm .

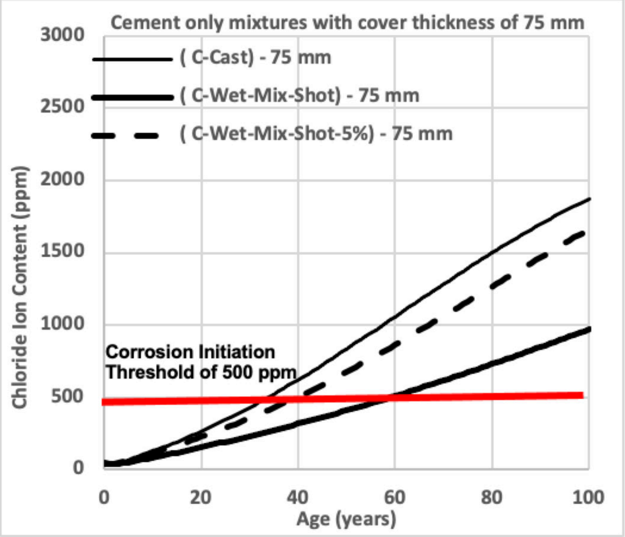

Fig. 2b) Chicago Bridge Structure chloride ion content development with time for cement only mixtures with cover thickness of 75 mm.

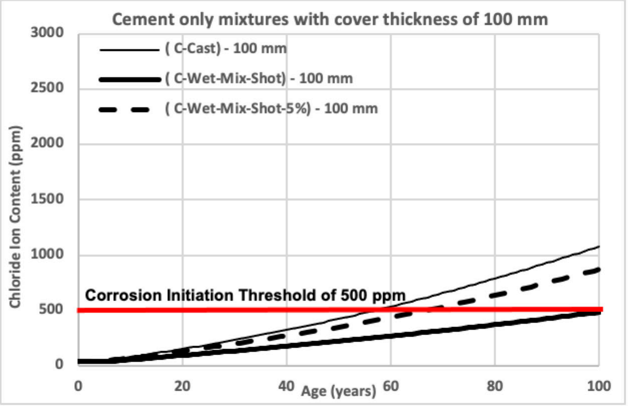

Fig. 2c) Chicago Bridge Structure chloride ion content development with time for cement only mixtures with cover thickness of 100 mm.

SCENARIO #1: MODELLING A CHICAGO BRIDGE STRUCTURE

The Chicago Bridge structure modeled represents a typical concrete structure in an urban area that is exposed to corrosion caused by de-icing salts (Fig. 2). This type of structure is representative of most bridge structures that are exposed to the long winter conditions which prevail in most of the northern, central, and eastern US states and most of Canada. Table 2 shows the exposure conditions that were input into the STADIUM® model for this structure.

Type	Average	Amplitude	Period	Period Offset	Duration
Relative humidity	62.50%	0.0%	365 days	0.0 days	
Air Temperature	9.0 C	14.0 C	365 days	0.0 days	
De-icing Salt	0.0 mmol/L	0.0 mmol/L	1.0 days	0.0 days	246.5 days
	0.0 mmol/L	300.0 mmol/L	110.0 days	246.5 days	55.0 days
	0.0 mmol/L	0.0 mmol/L	1.0 days	0.0 days	63.5 days

Table 2. Exposure Conditions for Chicago Bridge Structures

Figs. 2a), b), and c) show the total chloride ion content for cast concrete and wet-mix shotcrete mixtures with cement only, with cover thicknesses of 50 mm (2 in.), 75 mm (3 in.), and 100 mm (4 in.) respectively.

For the cement-only mixtures, at each cover thickness, the time for the chloride ion content to reach the corrosion initiation threshold of 500 ppm occurs more rapidly in cast concrete compared to wet-mix shotcrete.

Figs. 2a), b), and c) also show that the time to reach corrosion initiation increases by increasing the cover thickness from 50 mm to 75 mm, and to 100 mm. In particular, the time for wet-mix shotcrete with 100 mm cover thickness to reach the corrosion initiation threshold of 500 ppm chloride is about 100 years. This shows that shotcrete with appropriate cover thickness can achieve excellent service life in a de-icing salt exposure environment.

It should be noted that when accelerator is added at 5% by mass of cement, the rate of penetration of chloride ion increased from wet-mix shotcrete without accelerator to wet-mix shotcrete with accelerator. This shows that when accelerator is added, it will accelerate the time for corrosion initiation. However, the time to corrosion initiation for wet-mix shotcrete with 5% accelerator is still longer than that for cast concrete.

Figs. 3a), b), and c) show the total chloride ion content for cast concrete and wet-mix shotcrete mixtures with fly ash with 50 mm, 75 mm, and 100 mm cover thickness.

The rate of penetration of chloride ion for wet-mix shotcrete is slower than for cast concrete. When accelerator is added at 5% by mass of cement, the chloride ion content in the mix with fly ash increased at the fastest rate and is higher than in cast concrete. This shows that the addition of accelerator does increase the rate of chloride ion content penetration in wet-mix shotcrete with fly ash, and reduces the time for corrosion initiation.

Mix Type	**Cement ONLY**								
Placement Method	Cast			Shot Wet-Mix			Shot Wet-Mix with 5% Accelerator		
Mix Designation	A1	A1	A1	A3	A3	A3	A4	A4	A4
Concrete Cover (mm)	50	75	100	50	75	100	50	75	100
Time (years)	18	28	56	29	59	100	20	33	65
Mix Type	**Fly Ash modified**								
Placement Method	Cast			Shot Wet-Mix			Shot Wet-Mix with 5% Accelerator		
Mix Designation	B1	B1	B1	B3	B3	B3	B4	B4	B4
Concrete Cover (mm)	50	75	100	50	75	100	50	75	100
Time (years)	63	>100	>100	78	>100	>100	50	>100	>100
Mix Type	**Silica Fume modified**								
Placement Method	Cast			Shot Wet-Mix			Shot Wet-Mix with 5% Accelerator		
Mix Designation	C1	C1	C1	C3	C3	C3	C4	C4	C4
Concrete Cover (mm)	50	75	100	50	75	100	50	75	100
Time (years)	64	>100	>100	52	>100	>100	52	>100	>100

Table 3: Chicago Bridge with Wet-Mix Shotcrete & Cast in Place Concrete: Time to Reach 500 ppm Corrosion Threshold Limit (years)

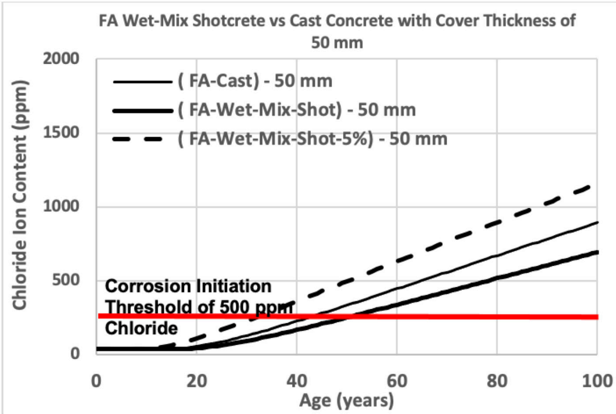

Fig. 3a) Chicago bridge structure chloride ion content development with time for fly ash mixtures with cover thickness of 50 mm

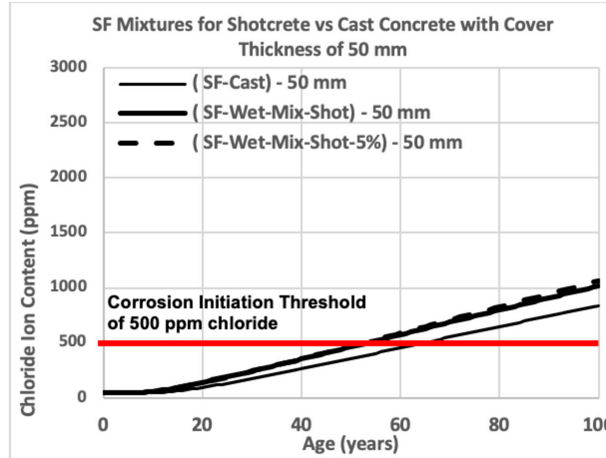

Fig. 4a) Chicago bridge structure chloride ion content development with time for silica fume mixtures with cover thickness of 50 mm

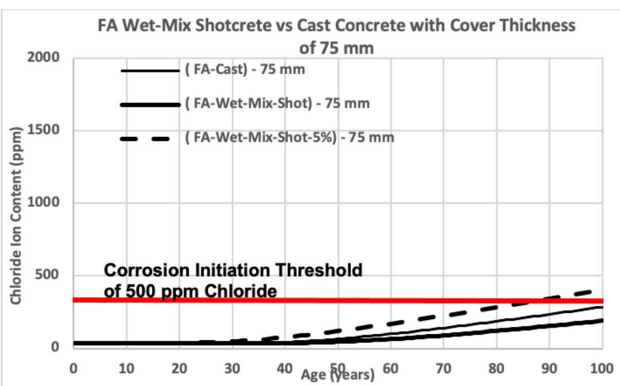

Fig. 3b) Chicago bridge structure chloride ion content development with time for fly ash mixtures with cover thickness of 75 mm

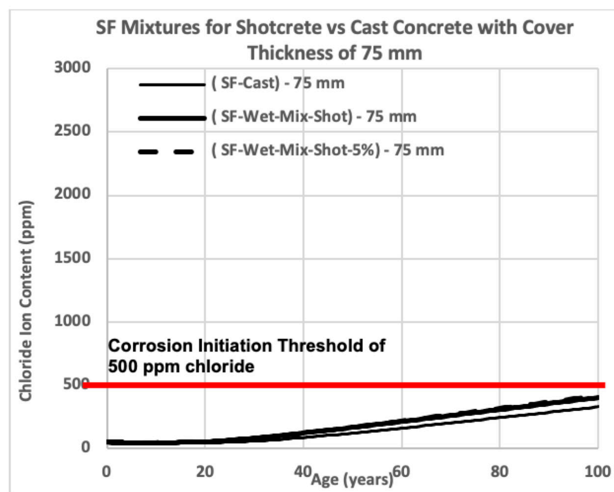

Fig. 4b) Chicago bridge structure chloride ion content development with time for silica fume mixtures with cover thickness of 75 mm

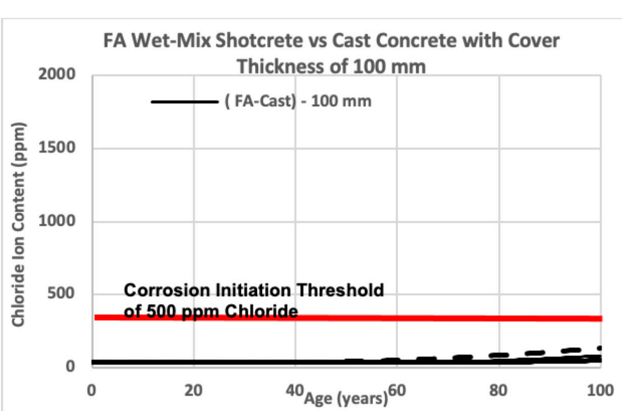

Fig. 3c) Chicago bridge structure chloride ion content development with time for fly ash mixtures with cover thickness of 100 mm

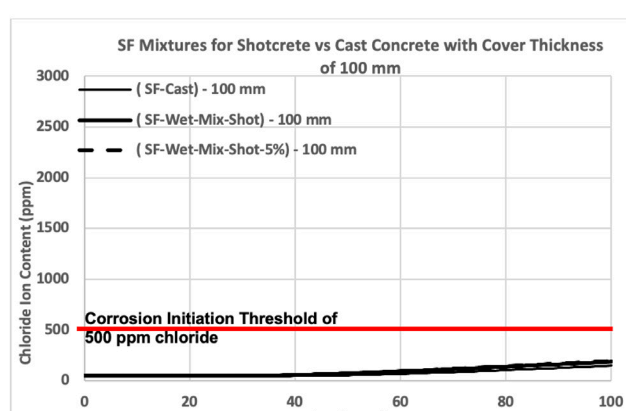

Fig. 4c) Chicago bridge structure chloride ion content development with time for silica fume mixtures with cover thickness of 100 mm

Note, however, that the shotcrete mixtures with fly ash have much greater times to initiation of corrosion than comparable cement-only mixtures.

Figs. 4a), b), and c) show the total chloride ion content for wet-mix shotcrete mixtures with silica fume with cover thickness of 50 mm, 75 mm, and 100 mm respectively.

Fig. 4a) shows that with a cover thickness of 50 mm, the time to corrosion initiation is about 52 years for both shotcrete and shotcrete with 5% accelerator, while it is about 63 years for cast concrete. The longer time to corrosion initiation is caused by the fact that silica fume wet-mix shotcrete has a higher coefficient of diffusion and effective coefficient of diffusion, than cast concrete with silica fume[1], which results in the reduced time to corrosion initiation in the shotcrete mixtures. Figs. 5b) and 5c) show that with cover thicknesses of 75 mm and 100 mm, the chloride ion content does not reach the threshold of 500 ppm at 100 years. This means that the time to corrosion initiation is longer than 100 years for cover thickness of 75 mm and above for all the silica fume mixtures.

SHOTCRETE VS. CAST-IN-PLACE CONCRETE

Figures 2a, b, c, 3a, b, c, and 4a, b, c and Table 2 show the development for total chloride ion profiles for cast concrete vs. wet-mix shotcrete for mixtures with cement only, fly ash, and silica fume respectively. These curves show that the chloride ion content for cast concrete mixtures develops more rapidly with time compared to shot wet-mix shotcrete without accelerator for mixtures with cement only and fly ash (Figs. 2a, b, c and Figs. 3a, b, c). When silica fume is used (Figs. 4a, b, and c), the cast concrete shows slightly better performance than shotcrete at 50 mm cover, and almost the same level of lower than 500 ppm at 100 years at both 75 mm and 100 mm cover. These figures clearly show that the shotcrete process can reduce the rate of migration of chloride ion penetration at cover thickness of 50 mm and above, and therefore delay the time for chloride to reach the threshold to cause corrosion initiation in cement only and fly ash mixtures.

CEMENT VS. FLY ASH VS. SILICA FUME

When comparing Figs. 2a, b, and c, 3a, b, and c, and Figs. 4a, b, and c, the effects of fly ash and silica fume on the time to corrosion initiation are significant. Results for reaching the threshold of 500 ppm are summarized in Table 3. These figures and table show that cast concrete and shotcrete mixtures with cement only have the highest total chloride ion content at 100 years while mixtures with fly ash and silica fume have substantially lower chloride ion contents. These results are consistent with the known reduction in permeability and subsequent improvement in durability when using fly ash and silica fume in the concrete industry.

MODEL SCENARIO #2: CAISSON STRUCTURE IN TAMPA, FL, EXPOSED TO SEA WATER IN THE TIDAL ZONE

The model of a caisson structure in Tampa, FL exposed to seawater in the tidal zone represents one of the most severe chloride exposure conditions for a reinforced concrete structure. The modelling analysis was conducted with concrete cover thicknesses of 50 mm, 75 mm, and 100 mm at ages up to 100 years. Fig. 5 shows the exposure conditions that were input into the STADIUM® model for this structure.

The salinity is about 35 ppt, which is about 35,000 ppm. Figs. 6a), b), and c) model results for total chloride ion content at cover thickness of 50 mm, 75 mm, and 100 mm are presented and discussed below.

The shotcrete mixture (without accelerator) shows the longest time to initiation of corrosion, followed by the cast concrete mixture, and then the shotcrete mixture with accelerator.

Figs. 7a), b), and c) show the chloride ion development with time of fly ash mixtures with cover thicknesses of 50 mm, 75 mm and 100 mm respectively.

The fly ash shotcrete mixture (without accelerator) has similar time to initiation of corrosion as the cast concrete mixture. The shotcrete with accelerator has the shortest time to initiation of corrosion. Comparing these results with the cement only mixtures shows that addition of fly ash prolongs chloride migration and therefore delays the time to initiation of corrosion. The effect of accelerator is discussed later in this paper.

Figs 8a), b), and c) show the chloride development with time of silica fume mixtures with cover thicknesses of 50 mm, 75 mm, and 100 mm respectively.

These figures show that for the silica fume modified mixtures the cast concrete has the longest time to initiation of corrosion, followed by the shotcrete mixtures with and without accelerator, which have similar times to initiation of corrosion. It was only in the silica fume modified mixtures where the cast concrete mix showed a longer time to initiation of corrosion than a shotcrete mixture.

The time to corrosion initiation for all the caisson

Type	Average	Amplitude	Period	Period Offset
Relative humidity	73.00%	0.0%	365 days	0.0 days
Air Temperature	22.0 C	6.0 C	365 days	0.0 days
Salinity	35.0 ppt (‰)	0.0 ppt (‰)	365 days	0.0 days

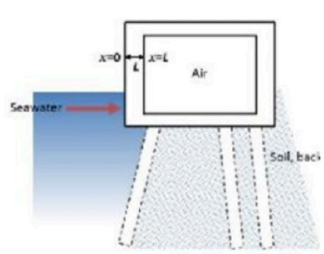

Fig. 5 Exposure Conditions of Caisson in Tampa, FL

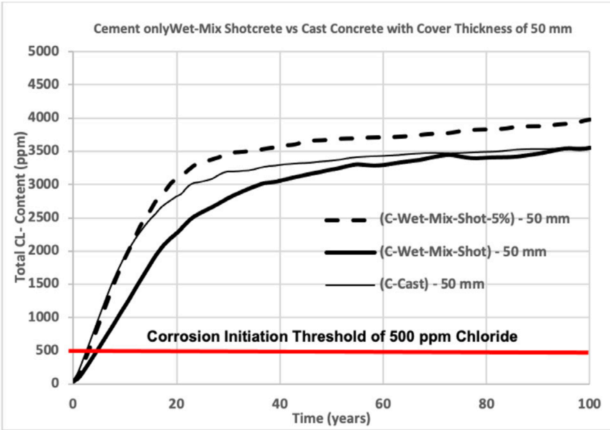

Fig. 6a) Tampa caisson structure chloride ion content development with time for cement only mixtures with cover thickness of 50 mm

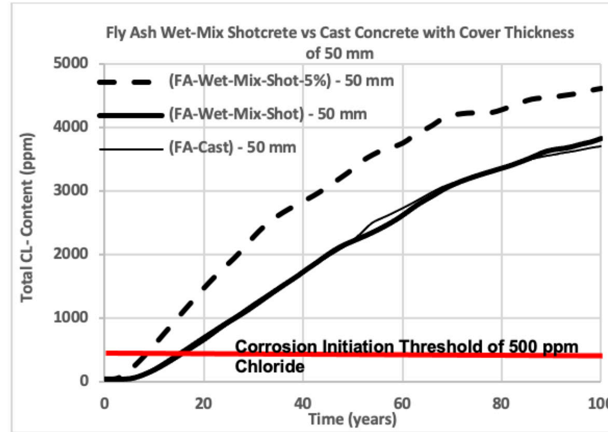

Fig. 7a) Tampa caisson structure chloride ion content development with time for fly ash mixtures with cover thickness of 50 mm

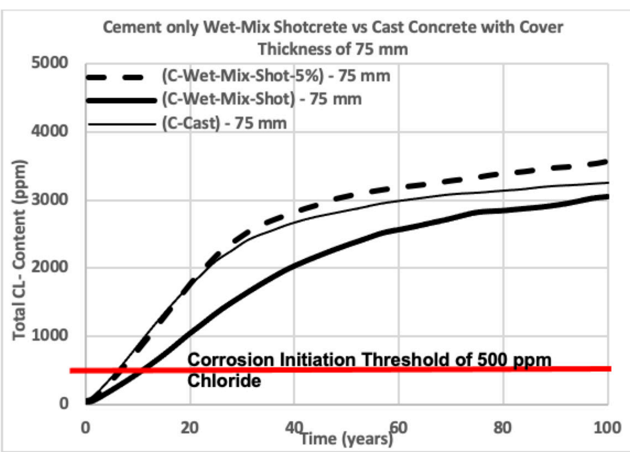

Fig. 6b) Tampa caisson structure chloride ion content development with time for cement only mixtures with cover thickness of 75 mm

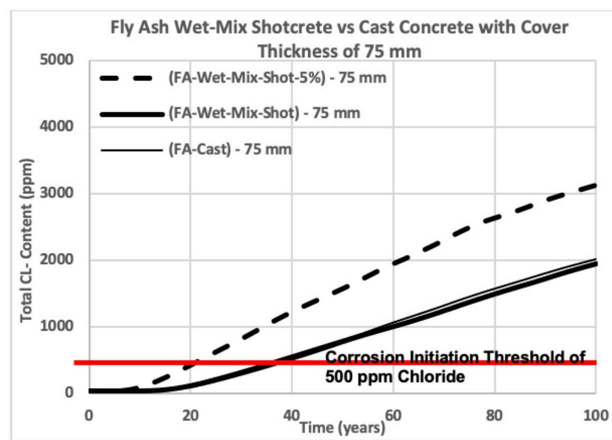

Fig. 7b) Tampa caisson structure chloride ion content development with time for fly ash mixtures with cover thickness of 75 mm

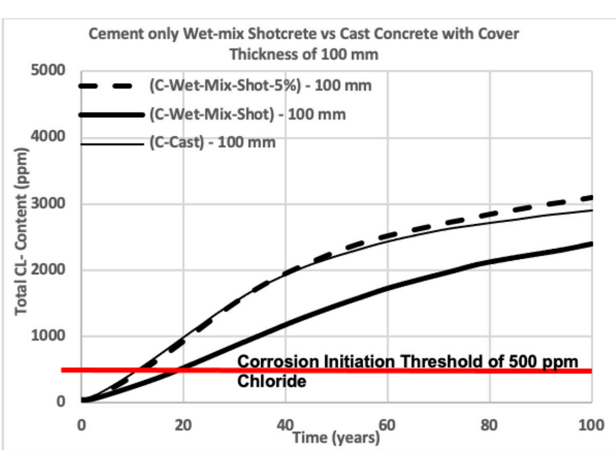

Fig. 6c) Tampa caisson structure chloride ion content development with time for cement only mixtures with cover thickness of 100 mm

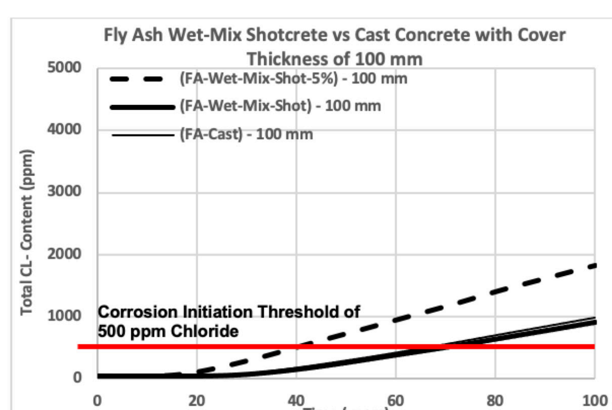

Fig. 7c) Tampa caisson structure chloride ion content development with time for fly ash mixtures with cover thickness of 100 mm

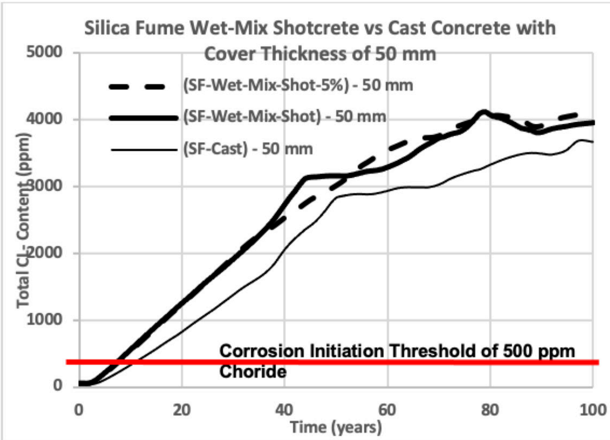

Fig. 8a) Tampa caisson structure chloride ion content development with time for silica fume mixtures with cover thickness of 50 mm

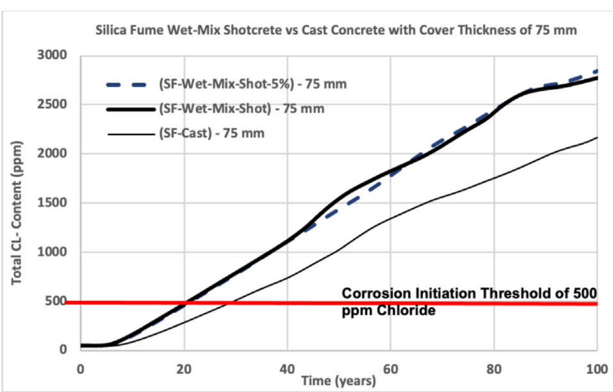

Fig. 8b) Tampa caisson structure chloride ion content development with time for silica fume mixtures with cover thickness of 75 mm

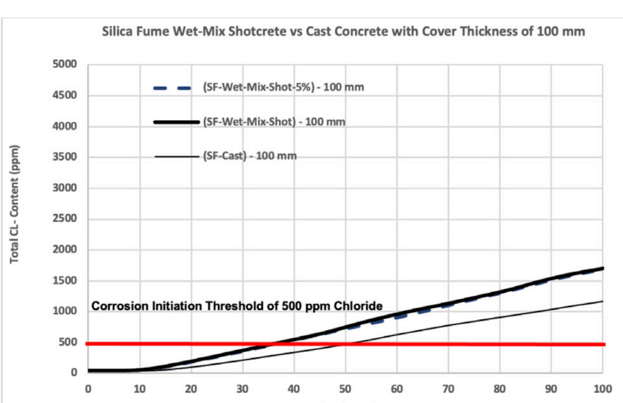

Fig. 8c) Tampa caisson structure chloride ion content development with time for silica fume mixtures with cover thickness of 100 mm

mixtures tested is summarized in Table 4.

SHOTCRETE VS. CAST CONCRETE

Table 4 shows the relationship between cover thickness and the time to initiation of corrosion in all the shotcrete and cast concrete mixtures. It shows that for cement only mixtures the shotcrete mixture without accelerator outperforms the cast concrete mix, while the shotcrete mixture with accelerator has similar performance to the cast concrete mix. In the fly ash mixtures the shotcrete (without accelerator) has similar performance to the cast concrete mixtures, but the shotcrete with accelerator has a lower time to initiation of corrosion. In the silica fume modified mixtures the cast concrete has the longest time to initiation of corrosion, followed by the shotcrete mixtures.

Best overall performance in this marine environment was provided by the fly ash mixtures. Fig. 9 shows the time to initiation of corrosion of the shotcrete (without accelerator) and cast concrete mixtures at different thicknesses of cover for the fly ash mixtures.

EFFECT OF RAPID-SET ALKALI-FREE ACCELERATOR

One should note that these types of accelerator are only useable with shotcrete placement. This opens up many marine applications with tidal changes in water level or underground projects that require a quick set and early strength gain. When accelerator is added to the shotcrete at the nozzle, chloride ion penetration develops at a faster rate with time. This occurs with the cement-only, fly ash and silica fume mixtures at cover thicknesses ranging from 50 mm to 100 mm. This is attributed to the fact that when accelerator is added, shotcrete experiences an accelerated hydration process, which results in a faster production of ettringite and less densified calcium silicate hydrate (CSH) microstructure. This results in an increased permeability and coefficient of diffusion[Ref. 1], allowing a faster rate of chloride ion migration into the concrete.

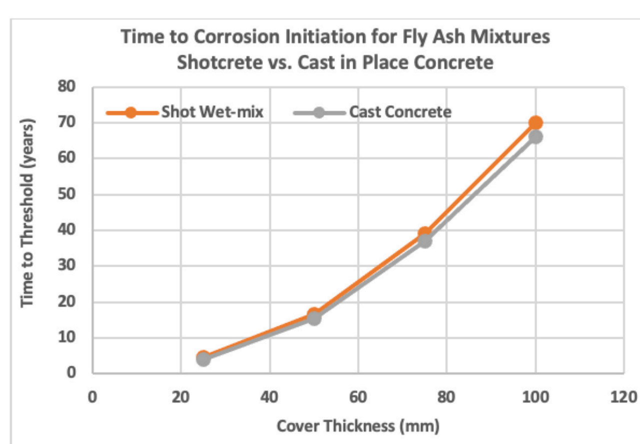

Fig. 9 Time to reach corrosion threshold of 500 ppm with increasing cover thickness in fly ash mixtures.

Mix Type	Cement ONLY								
Placement Method	Cast			Shot Wet-Mix			Shot Wet-Mix with 3% Accelerator		
Mix Designation	A1	A1	A1	A3	A3	A3	A5	A5	A5
Concrete Cover (mm)	50	75	100	50	75	100	50	75	100
Time (years)	4	8	11	6	11	20	4	8	11
Mix Type	**Fly Ash modified**								
Placement Method	Cast			Shot Wet-Mix			Shot Wet-Mix with 3% Accelerator		
Mix Designation	A1	A1	A1	A3	A3	A3	A5	A5	A5
Concrete Cover (mm)	50	75	100	50	75	100	50	75	100
Time (years)	15	38	68	15	38	70	8	21	40
Mix Type	**Silica Fume modified**								
Placement Method	Cast			Shot Wet-Mix			Shot Wet-Mix with 3% Accelerator		
Mix Designation	A1	A1	A1	A3	A3	A3	A5	A5	A5
Concrete Cover (mm)	50	75	100	50	75	100	50	75	100
Time (years)	14	30	50	9	21	35	9	21	35

Table 4: Tampa Caisson with Wet-Mix Shotcrete & Cast in Place Concrete: Time to Reach 500 ppm Corrosion Threshold Limit (years)

CONCLUSIONS

Modelling results for the bridge structure in Chicago, which is exposed to the de-icing salts, and the caisson structure in Tampa, which is exposed to the tidal salt water, show that these two structures have the following features in common:

- With a single exception (silica fume shotcrete in caisson structures), cast structural concrete produces the shortest time to reach the chloride threshold of 500 ppm, beyond which corrosion initiation starts. When wet-mix shotcrete (without accelerator) was used, the time to reach the threshold of corrosion initiation increased compared to cast concrete for mixtures with cement as the only binder. In fly ash modified mixtures the performance was similar between cast concrete and shotcrete mixtures. This shows that the shotcrete process delays the time for the chloride ion content to reach the limit for corrosion initiation. This also shows that properly applied shotcrete will extend the service life of the structures in de-icing salt and marine exposure in the tidal zone.
- Time to corrosion initiation increases with cover thickness from 25 mm to 100 mm in a non-linear relationship. This is as expected.
- There are different mechanisms causing corrosion initiation. These involve permeability, porosity, diffusion, and chloride ion penetration resistance. Changing mixture designs, including using fly ash or silica fume and using shotcrete vs. cast concrete, affects these mechanisms differently when subjected to different exposure conditions. The time to corrosion initiation will vary from exposure in a bridge environment with deicing salt and a marine structure. The effects of these mechanisms on the time to initiation of corrosion needs to be evaluated by laboratory testing, modelling, and field tests to validate service life prediction models.

IN SUMMARY

When properly designed and applied, wet-mix shotcrete provides equal or increased service life for reinforced concrete structures compared to cast concrete. The addition of supplementary cementitious materials (such as fly ash and silica fume) is recommended, as it further extends the service life. Cement-only cast concrete and shotcrete mixtures have lower resistance to chloride ion penetration and reduced service life and are thus not recommended in chloride exposure environments.

The modelled results provide a comprehensive database for the expected performance of different types of cast and shotcreted mixtures for different exposure conditions.

RECOMMENDATIONS FOR FUTURE DEVELOPMENT

Much more complex reinforced concrete structures are now being built or repaired with shotcrete[4][5][6]. Shotcrete is a technology which involves both materials and application processes. Understanding the service life of shotcrete is critical. This paper provides a basic framework, based on which a guide for service life prediction for structures built or repaired with shotcrete can be developed. In the future, the authors are planning to develop a basic guideline for shotcrete service life prediction for a range of different exposure environments.

A proposed outline for the basic guideline includes:

a. Design suitable mixtures for the selected exposure environment and conduct trial shooting with proper preparation of test samples This process also requires appropriate equipment selection (wet-mix or dry-mix process) and shooting test panels by qualified shotcreters (minimum ACI certified shotcreter).
b. Conduct laboratory testing to obtain the necessary shotcrete transport properties data required for input into the service life model. The minimum required tests to be conducted include compressive strength to ASTM C39, ASTM C642, ASTM C1792, and ionic migration tests.[1] These tests should be conducted at least at 28 and 56 days age.
c. Model the service life with the test results. The modelling process requires input on structure locations, environmental exposure conditions, required service life, details of reinforcement (including concrete cover) and some other required information. Although there are some other service life prediction models available, it is recommended that the STADIUM® model be used.

For structures where service life modelling and prediction is not critical, but designers/engineers would like to know the service life potential when using shotcrete, a simplified method could be used. This would involve conducting shotcrete trials with test panels, extracting cores and conducting tests for at least, compressive strength, boiled absorption and ionic migration, and referring to the service life prediction data presented in this research paper (and additional data to be presented in a future paper). Comparing the results of this data to the data in this paper should provide an approximate indication of the potential service life for the selected structure and exposure conditions.

Tested and modelled results should be able to show that for most environmental exposure scenarios, shotcrete, when properly deigned and applied, is able to provide equivalent or extended service life compared to cast-in-place concrete. Cost analysis based on service life analysis can be conducted to estimate the life cycle costs of a project.

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