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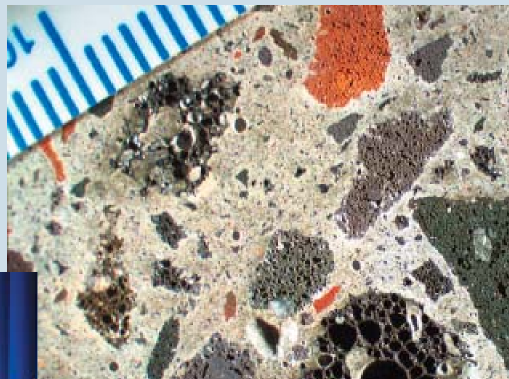

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Synopsis: Ten concrete ships currently being used as a floating breakwater around the log pond at the Pacific Paper Powell River plant in British Columbia, Canada, are after approximately 55 to 80 years of marine exposure, showing varying degrees of deterioration. The ships were constructed with a double mat of reinforcing steel and expanded lightweight shale aggregate concrete. Two separate inspections were conducted over the last seven years to evaluate the conditions of the hulls, decks, and other components of five of the ships. Cores taken from various portions of the ships with different exposure conditions were subjected to laboratory analysis and testing, including testing for compressive strength and petrographic examination. Results of these tests indicate that the lightweight aggregate concrete that the ships are constructed of has performed well, considering the harsh marine environment to which they are exposed. All the ships exhibited evidence of spalling induced by the corrosion of embedded steel reinforcement. However, the extent and severity of spalling varies between ships and was influenced by the depth of concrete cover over the reinforcement, the development of structurally-related cracking in the ships' hulls and decks, and the penetration of air, moisture, and salts to the level of the reinforcing steel. Lightweight aggregate concrete in parts of the ships not exhibiting delaminations are in generally good condition and the cement matrix exhibits a tight microstructure and apparent low permeability to seawater. The manufactured lightweight aggregate used in the concrete is essentially unchanged proving that it is durable in a harsh marine environment. Compressive strength of the concrete meets or exceeds the designed minimum compressive strength of 35 MPa (5000 psi). Overall, the lightweight aggregate concrete is of excellent quality and has performed well for over 50 years.

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INTRODUCTION

This paper describes the findings of recent studies of five reinforced lightweight concrete ships built between 1920 and 1945 and the general performance of the lightweight aggregate concrete after 55 to 80 years of exposure to a harsh marine environment. The five ships were chosen from a group of 10 vessels comprising a floating breakwater around a log pond in Georgia Straits at Pacific Paper's Powell River pulp and paper plant in British Columbia, Canada (Fig. 1). One of the ships evaluated in these studies is the ***Peralta***, a tanker constructed in 1920. Other ships studied include the ***Emile Vidal***, the ***Armand Concidere***, the ***Yogn***, and the ***P.M. Anderson*** which were constructed during the Second World War.

Although details of the design and construction of concrete ships and the materials used in their construction are available, specific information related to these particular ships and their use over the last 50+ years is somewhat limited. Several articles have been published about the early concrete ships and their performance in a marine environment (1, 2). Most notably, the ***USS Selma***, sunk and partially submersed in seawater off the coast of Texas, has been mentioned in several studies of the performance of lightweight aggregate concrete in a marine environment. The ***Peralta*** was built in 1920 by the San Francisco Shipbuilding Co., Oakland, California (3). The other ships at the Powell River site were constructed about 1943 and were the tankers ***Emile Vidal***, ***Armand Concidere***, and ***P. M. Anderson*** and the barge ***Yogn***.

Two recent studies have been conducted to evaluate the condition of the Powell River ships and performance of the lightweight concrete of which they are constructed. In the first site investigation, conducted in 1992 by AGRA Earth & Environmental Ltd., three of the ten ships were inspected as part of a condition survey for a previous owner of the ships MacMillan Bloedel Ltd. (4). The study was conducted mainly to provide confidence to the owners that the ships were of adequate condition to continue to function as a floating breakwater. This study involved inspection of three ships including the oldest ship, the ***Peralta***, and the most deteriorated ship, the ***Emile Vidal***. The ***Peralta*** represents one of the early applications of lightweight aggregate concrete in the construction of a large ship. Portions of the exposed exterior surfaces of this ship, including the hull and deck, developed severe surface spalling in localized areas caused by corrosion of embedded steel reinforcement. As a result of this deterioration, most of the hull surface was repaired in 1968 using shotcrete. The ***Emile Vidal*** was used as a dry cargo vessel and once held large quantities of salt in the hold. This ship developed extensive corrosion of embedded steel and associated spalling of the hull and deck exacerbated by infiltration of salts from the hold into the concrete. The ***P.M. Anderson***, judged to be in a condition typical of the remaining ships, was also inspected.

The 1992 investigation involved visual inspection of the ships, sounding of the hull for evidence of delamination, coring for samples for compressive strength, determination of depth of carbonation, chloride ion profiling, and copper-copper sulfate half-cell potential testing. Some limited underwater inspection of the hull was conducted along the leeward side of two vessels to determine if delamination has occurred below the water line. Following this 1992 investigation, some shotcrete repair was done on portions of the interior hull and hatch structures of the ***Emile Vidal***.

The second study of the Powell River ships was conducted in October 1998. Four of the ships, namely the ***Peralta***, ***Emile Vidal***, ***Armand Concidere***, and ***Yogn*** (Fig. 2) were inspected and core samples were extracted from hulls, decks, and selected above-deck structures. The below deck, interior chambers of the ships were not directly inspected, however, some limited viewing of below-deck structures was made through hatches and other openings in the top deck. The general condition of the exterior of the ships, particularly the hulls, decks, and above-deck structures, was recorded and photo-documented. Cores were taken from selected hulls, decks, and hatches, as well as one column and one cabin wall. With the exception of one interior column, cores were taken from structures exposed to seawater or sea spray and rainwater. These cores were later subjected to petrographic examination, compressive strength testing, or both. This later inspection was conducted on behalf of the Expanded Shale, Clay and Slate Institute as part of an ongoing study of the durability of lightweight aggregate concrete exposed to a marine environment.

SIGNIFICANCE

Study of the Powell River ships provides an excellent opportunity to evaluate the long-term performance of lightweight aggregate concrete in a marine environment. The lightweight aggregate concrete used to construct these ships varies in age and composition and (with exception of the ***Emile Vidal***) was exposed to normal to severe marine environment for approximately 55 to 80 years. The concrete ships were exposed to seawater, heavy wave action and related cyclic stressing, and due to the geographic location in which they are kept, periods of cyclic freezing and thawing. The ships have also been intentionally heeled inward towards the log pond to increase their effectiveness as a floating breakwater.

Additionally, the study of the different lightweight aggregates used in the construction of these ships provides an insight into the characteristics, general performance, and apparent changes and improvements achieved in nearly a century of manufacturing man-made lightweight aggregate.

INVESTIGATION AND OBSERVATIONS

Overall, the inspection revealed the ships to be in generally good condition considering the minimal maintenance and harsh environment in which they are kept. Currently the ships exhibit varying degrees of deterioration mostly related to spalling of concrete cover over corroded steel reinforcement (Fig. 3). The hull of several of the ships exhibits numerous diagonal structural cracks, particularly apparent near the bow and stern thirds of the ships. Such cracks likely formed from cyclic loading and stressing of the ship. The bows and sterns of the ships also exhibit damage reportedly caused by incidental impact with the other ships during storms. This structural cracking and damage has allowed air, moisture, and sea salts to locally penetrate to the level of embedded reinforcement, promoting corrosion of the steel bars and subsequent spalling of the concrete cover. Deterioration on the ***Emile Vidal*** has also been accelerated by exposure of the concrete to stored salts in the holds. It is important to note, however, that with exception of the ***Peralta*** and ***Emile Vidal***, and despite having cover of approximately 7/8", far less than current ACI 318 requirements, most of the hulls on the majority of the ships are not extensively spalled, particularly on the more protected, leeward side.

Limited underwater inspection conducted in the 1992 study revealed mostly isolated spalling of the hull below the water line. Spalling also appears to be more severe on the windward sides of several ships. This is particularly evident on the ***Yogn***. The windward side of the ***Yogn*** (facing southwest towards Georgia Strait) typically experiences heavier wave action and more frequent exposure to the sun than the shaded, protected leeward side. Such conditions likely resulted in more frequent thermal cycles and cycles of wetting and drying.

Removal of loosely attached, partially spalled surface concrete typically exposed the outer mat of steel reinforcing bars. The outer face of these exposed bars exhibits mild to severe corrosion of the steel. However, the backsides of many of these bars, exposed during coring, exhibit only mild to negligible corrosion (Fig. 4). Cores taken through several of the diagonal cracks on the hull of the ***Armand Concidere*** and ***Yogn*** also revealed only minor to negligible corrosion of steel reinforcing bars intersected by these cracks (Fig. 5). Overall, most inspected sections of embedded steel bars exposed by coring in sound areas of concrete show mostly minor to negligible corrosion of the steel bars.

Visual inspection and sounding of other above-water concrete surfaces also revealed localized spalling of the concrete deck and deterioration of corners and edges of hatches and cabin structures in a few ships. Such damage is most evident along portions of the exterior deck of the ***Peralta*** and the ***Emile Vidal***. Exterior surfaces of decks, cabin structures, and hatch openings on the other inspected ships are in good condition. Limited inspection of the interiors of cabins and other concrete structures protected from rain and harsh conditions reveals most surfaces of interior decks, walls, columns, and beams exhibit little to no evidence of distress or deterioration (Fig. 6). Many of these concrete surfaces still exhibit the imprint of the original wood forms used during construction.

Horizontal surfaces exposed to the elements, such as decks, sills, and cabin roofs, exhibited variable weathering and deterioration. In most of these examined horizontal surfaces the cement binder has eroded more extensively than the lightweight aggregate, resulting in a roughened surface texture with aggregates exposed in low to moderate relief. Aggregate exposed by weathering is generally hard, firm and apparently quite durable. This weathering effect is attributed to prolong exposure of the concrete to mildly aggressive components in rain and seawater. Exposure to aggressive organic acids related to the growth of algae and lichen and breakdown of bird droppings also likely contributed to the erosion of the concrete surfaces. Later microscopical examination of several deck cores revealed localized leaching of calcium and other elements from the surface paste and faces of cracks and delaminations, particularly on the deck of the ***Emile Vidal***. However, examination of deck, hull, and hatch cores from the other ships revealed negligible leaching of calcium from the surface paste.

The shotcrete used in the repair of the ***Peralta*** in 1968 and the ***Emile Vidal*** in 1992 currently appears to be in fair to good condition. However, some localized delamination is evident along the bond line of the shotcrete on the hull of the ***Peralta***. Delamination was likely promoted by less than ideal preparation of the repair surface prior to shotcrete application and continued corrosion of previously corroded steel reinforcement. Several cores obtained from repaired hatches on the ***Emile Vidal*** where extended through the attached shotcrete. Examination of these cores revealed the shotcrete is well adhered to the older surfaces with no visible signs of debonding.

The ***Armand Concidere*** is judged to be in the best condition of the four inspected ships. The hull exhibits only minor spalling of surface concrete and exposure of corroded steel bars, mostly at and just above the water line. The deck, hatches and cabins are in generally good condition with minimal spalling and delaminations.

The ***Yogn*** is also judged to be in fairly good condition with mostly localized shallow spalling of the hull. Most of the spalling occurs just above the existing water line. Sounding of concrete surfaces adjacent to spalled areas revealed additional incipient spalling of the concrete cover along the hull. However, most of the hull well above the water line is in good condition. As best as could be determined from above water observations, the hull below the water line also appears to be in good condition. The deck of the ***Yogn*** has a normal weight concrete topping. Large sections of this topping exhibit extensive cracking and heaving, locally exposing what appears to be the original lightweight concrete deck. Where exposed, the underlying deck appears to be in good condition. Other above-deck concrete structures also appear to be in good condition.

Laboratory Analysis of Cores

Petrographic examination was performed on cores taken from the hull of the ***Yogn*** and ***Armand Concidere*** as well as decks and selected vertical structures of the ***Peralta***, ***Emile Vidal***, and ***Armand Concidere***. One core extracted from a column in the interior of a cabin on the ***Peralta*** was also examined petrographically to study the condition of concrete mostly protected from rain and seawater. Cores subjected to petrographic examination were initially examined visually and using a stereomicroscope for any evidence of cracking, alteration, or general distress. Selected areas of some cores were treated with epoxy resin to preserve delicate features and to keep cracked cores intact during dissection. Each of the cores were saw-cut longitudinally and one of the resulting cross sections of each core was finely ground (lapped) and examined using a stereomicroscope at magnifications up to 45X. Freshly broken surfaces of concrete were also studied using the stereomicroscope. Petrographic thin sections were produced from several of the dissected cores and examined using a polarized light microscope at magnifications up to 400X to study paste and aggregate mineralogy and microstructure.

The depth of cement paste carbonation was determined in each core subjected to petrographic examination as well as well as several other cores. The depth of carbonation was initially determined using a pH indicator solution (phenolphthalein) applied to freshly broken or saw cut surfaces during inspection of the ships. This technique is a rapid and reliable method of determining the extent of carbonation in concrete (5). The extent of carbonation was later confirmed during visual examination of saw-cut surfaces and microscopical examination of concrete specimens in thin section.

Seven cores were selected for physical testing to determine compressive strength of the concrete. These cores include three cores taken from the hulls of two ships (***Armand Concidere*** and ***Yogn***), two cores from the vertical combing of hatches on the top deck, one core from a top deck, and one core from an interior column. The limited number of samples subjected to compression testing was due to the difficulty in obtaining cores free of reinforcing steel, hairline cracks, and of sufficient length for testing. The decks and hulls of the ships are heavily congested with closely spaced steel reinforcing bars with shallow cover. Coring yielded few cores of sufficient length-to-diameter ratio for compression testing. Fortunately, core testing performed during the 1992 study of these ships provided additional information concerning the compressive strength of the hull concrete.

The following observation and findings are based on the results of the laboratory examination and testing of the selected cores.

Petrographic Observations

The findings of the petrographic examinations confirmed the ships were constructed using manufactured, lightweight aggregate concrete, however, some differences in the characteristics and appearance of the lightweight aggregate were noted. Excluding damage associated with corrosion of steel reinforcement, the concrete and appearance of the aggregates used in the concrete, varied from good to excellent condition. Most cracking or evidence of distress is attributed to structural causes or corrosion of embedded reinforcing steel where the concrete cover is less than

25 mm (1 in.). Minor shrinkage-related microcracking is evident in several cores, particularly those taken from the ***Peralta***. However, the cracks are tight and the degree of microcracking is not deemed as excessive or indicative of a serious materials-related problem.

Some major differences are observed in the concrete samples taken from each of the ships. Most notable is that normal weight fine aggregate was used in the ships constructed in the 1940's whereas in the Peralta, launched in 1920, both the fine and coarse aggregates were lightweight. Density of concrete samples taken from the ***Peralta***, containing only lightweight aggregate, ranged from 1700 to 1720 kg/m^3 (106 to 107 pcf). Cores taken from the other ships, containing lightweight coarse aggregate and normal weight fines, were higher, ranging from 1830 to 2080 kg/m^3 (114 to 130 pcf).

The concrete used in the construction of the ***Peralta*** contains black to dark brown, partially crushed, expanded shale aggregate, 6 to 10 mm (1/ 4 to 3/8 in.) top size, uniformly dispersed in a non-air-entrained portland cement matrix (Fig. 7). No natural rock or sand was observed in the concrete samples taken from this ship. The vesicular lightweight aggregate is mostly angular to subangular and highly porous with pore sizes ranging up to 1 mm. The lightweight fines are angular fragments of the manufactured aggregate and include some small, glassy particles exhibiting few visible voids.

The cement paste is hard and dense, and paste-aggregate bond is of good quality. Paste volume is high, estimated at 30 to 35%, suggesting the mix was rich in cement. Most of the cement clinker has been fully hydrated from initial mix water and continued exposure to moisture in service. However, some coarse particles of partially hydrated cement clinker are still observed in the cement matrix. These partially hydrated clinker particles represent the coarsest fraction of the cement. The presence of some coarse clinker particles, ranging in size up to 0.2 mm, is typical of the coarsely ground cements used in the early 1900's. It is interesting to note that even the concrete column within a cabin in the ***Peralta***, which has been mostly protected from rain and seawater, shows evidence of continued and almost complete hydration of the cement clinker. Apparently, the concrete was either subjected to sufficient atmospheric moisture and sea spray in 80 years of marine exposure or the internal initial moisture in the lightweight aggregate to keep the internal relative humidity sufficiently high to enable the hydration process to continue to completion.

Cement paste microstructure is consistent with that normally observed in concrete exposed to harsh conditions. Microcracks are observed in several cores but are not particularly abundant. Most are confined to paste-rich areas of the concrete. The presence of such microcracks is not unusual in concrete exposed to thermal and flexural stresses, as would be expected on these ships. Paste adjacent to some near-surface cracks and microcracks exhibit some apparent leaching of soluble elements (mostly calcium hydroxide) from the cement paste. Most of the cement matrix, however, exhibits numerous evenly distributed portlandite (calcium hydroxide) crystals, even at and near the exterior surfaces.

The concrete used in the construction of the ***Emile Vidal***, and ***Armand Concidere*** are similar in appearance and general composition. Each consists of a light brown to light gray expanded shale or clay aggregate, 13 mm (1/2 in.) top size, and siliceous sand uniformly dispersed in a non-air-entrained portland cement matrix (Fig. 8). The lightweight aggregates are rounded to subangular, vesicular, and highly porous. Few manufactured aggregates of low porosity are noted. The normal weight sand consists of angular to subrounded grains comprised mostly of quartz, feldspar, granite, and other siliceous rocks and minerals. The cement paste is hard and dense. Aggregates are well bonded to the cement matrix. Most of the portland cement clinker has been fully hydrated with only traces of unhydrated clinker observed in the paste matrix.

Cores taken from the ***Yogn*** (Fig. 9) contain lightweight, expanded shale coarse aggregate of nominal 10 mm (3/8 in.) top size that differs in appearance from that observed in the ***Emile Vidal*** and ***Armand Concidere***. Otherwise, the concrete samples taken from the hulls of these ships exhibit similar siliceous, normal weight sand and similar micro-structural features in the cement paste.

Microcracks are fairly scarce in the concrete samples taken from the 1940's ships. The minimal microcracking evident in the concrete could be attributed to similarities in elastic stiffness and other physical properties of the lightweight aggregate and the cement matrix (2, 6). Small gaps and tear-like features are noted in the cement paste and along the periphery of several aggregates. These features likely resulting from plastic deformation and settlement of the plastic concrete when the ships were constructed. It is interesting to note that most of these gaps and tears are filled with portlandite (Fig. 10) and the affected aggregates are well bonded to the cement paste. Some autogenous healing is also apparent in several older hairline cracks in the concrete.

Portions of the lightweight aggregate in the ***Peralta*** concrete exhibit evidence of a paste-aggregate reaction (Fig. 11). Apparent paste-aggregate reactions are also noted, but to a lesser degree, in several of the cores taken from the other ships. Similar reactions have been previously observed in other studies of lightweight concrete structures exposed to harsh conditions (7). Some of these reactions have produced reaction products, including minor amounts of a clear, amorphous reaction gel. These deposits are observed mostly within voids along the peripheral region of the porous manufactured aggregate. Paste adjacent to several of these lightweight aggregates appears to be cloudy when viewed in thin section, further attesting to reactions along the paste-aggregate interface. However there is very little evidence of disruption or cracking along the aggregate periphery and the aggregate is well bonded to the cement matrix. Many of the lightweight fines observed in the cores appear to have also undergone a reaction. Such paste-aggregate reactions are believed to be mostly pozzolanic in nature and tend to improve adhesion of cement paste to the lightweight aggregate. Occurrences of deleterious, expansive paste-aggregate reactions are scarce, and where they occur, are largely confined to the cement paste immediately surrounding the affected aggregate. Apparently, the internal restraint of the concrete and the availability of near surface pores in the vesicular aggregate are sufficient to accommodate such minor expansive reactions. The composition of the reaction gel may also be of a less expansive nature. Furthermore, the fines of the lightweight aggregate have also undergone a beneficial pozzolanic reaction similar in nature to some glassy mineral admixtures commonly used in many modern concretes.

Reaction products are scarce in cracks and microcracks in the cement paste away from aggregates, although other crystalline deposits, including some ettringite and carbonate compounds are observed in some cracks and voids. These secondary deposits are not believed to be directly associated with any distress in the concrete and likely precipitated in cracks and voids from mineral-rich pore solution in the concrete.

Carbonation of the cement paste in the examined ships is judged to be shallow considering the age of the concrete. The cement matrix in most portland cement concrete has an inherently high pH (typically greater than 11). This high pH is beneficial to reinforced concrete and helps to protect embedded steel reinforcing bars from corrosion. Carbonation of cement paste reduces the concrete pH and makes the concrete less protective to the steel reinforcement. Carbonation and chloride ion penetration are two major contributors to reinforcement corrosion problems in concrete. Inspection of the ship structures revealed that the most extensive corrosion and spalling occurs where diagonal structural cracks are present and concrete cover over the reinforcement is shallow, locally less than 25 mm (1 in.) along portions of the ship decks and hull. This shallow cover and the presence of surface hairline cracks and microcracks in the concrete allowed more ready penetration of air, moisture, and salts to the reinforcement, promoting corrosion of the reinforcing steel. The findings of the ship inspection and laboratory examination of core samples indicates that the formation of hairline surface cracks is the main factor in instigating corrosion, particularly along the ship hulls. Application of a pH indicator solution to freshly broken cross sections of spalled concrete revealed much of the cement paste between the exposed exterior surfaces and the surface of delamination is not carbonated. Furthermore, laboratory testing of cores extracted from sound and partially delaminated areas of the ships revealed that the depth of paste carbonation is typically very shallow (Table 1). The concrete structures on the ***Peralta*** exhibit a comparatively greater depth of carbonation than the ships constructed in the 1940's. Carbonation typically extends to a depth of 1 to 5 mm from the exterior end surfaces of the cores taken from the deck and walls of the ***Peralta***. The greatest depth of carbonation observed in the collected samples occurred along the formed exterior surfaces of an interior column core on the ***Peralta***, where carbonation extends to a depth of 30 mm. The depth of carbonation along the exterior surfaces of essentially all of the cores taken from the ***Emile Vidal***, ***Armand Concidere***, and the ***Yogn*** is typically 1 mm or less. Holms, et al. (8) found similar minimal depth of carbonation in other concrete ships of similar ages. Slight carbonation is also noted along the faces of several hairline cracks and microcracks extending from these surfaces, but is also generally less that 1 mm deep. This minimal depth of carbonation attests to the low permeability of the cement matrix.

Compressive Strength Testing

Physical tests were performed on cores taken from the four inspected ships during the 1998 studies. Findings of these tests are given in Tables 2a and 2b. Testing of the cores taken above the water line (decks, hatch combings, and an interior column) yielded compressive strengths in excess of the minimum design strength of 34 MPa (5000 psi). Cores taken from the hull of the ***Yogn*** and ***Armand Concidere***, at or near the waterline, indicated considerably higher strengths, yielding an average compressive strength of 55 MPa (8000 psi). These strengths are consistent with the findings of the 1992 study in which cores taken from the hulls of the ***Peralta***, ***Emile Vidal***, and the ***P.M. Anderson*** yielded an average compressive strength 55 MPa. The higher strength of the hull concrete is attributed to the high cement factor used in the mixes and continued curing and maturation of the cement paste microstructure due to prolonged exposure of the concrete to moisture.

CONCLUSION

Inspection of the Powell River ships and laboratory analysis and testing of cores taken from these ships has revealed that the lightweight aggregate concrete has performed well in a relatively harsh marine environment after over 50 years of exposure. Inspection of the ships' exteriors revealed a varying degree of deterioration, mostly involving corrosion of near-surface steel reinforcement and spalling of the concrete cover. Corrosion and related spalling is most severe in ships exhibiting cracks and where the concrete cover over reinforcing steel is shallow. Structural diagonal cracks which have formed along the hull of several ships are believed to have been caused by cyclic loading and stressing. These cracks allow chlorides in seawater and oxygen to penetrate to embedded reinforcement, promoting localized corrosion of the reinforcing steel. Deterioration of the ***Emile Vidal*** is considerably more severe compared to other ships of similar age, due mainly to exposure of the concrete to stored salts. The studies have also indicated a clear correlation between corrosion activity and the extent of carbonation in the concrete. Overall, the rate and depth of carbonation in the concrete is minimal and most of the inspected steel reinforcing bars away from badly spalled areas are in good condition.

The inspected ships are constructed of lightweight aggregate concrete containing a variety of manufactured aggregates of differing age and microstructural characteristics. Microscopical examination of the concrete revealed evidence of continued hydration and development of the cement matrix. This continued maturation of the concrete has contributed to the development of compressive strengths in the ships' hulls well beyond the minimum design strength of the concrete. Microcracking is minimal and mostly related to structural and thermal stresses. The concrete is not air entrained, yet vertical surfaces exposed to cycles of freezing and thawing and wetting and drying exhibit little evidence of damage. Paste-aggregate bond is consistently excellent in all of the examined concrete specimens, in part attributed to mostly beneficial reactions along the paste-aggregate interface. The aggregate has remained hard, firm, and durable.

Overall, the manufactured lightweight concrete used in the construction of the ships has performed exceptionally well in a harsh marine environment.

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Table 1
Depth of Carbonation in Various Structures
On the Powell River Ships (1998 Study)

Core No.	Ship	Structure	Depth of Carbonation[1]
P-1	***Peralta***	Cabin Wall	Less than 1 mm [2,3]
P-3	***Peralta***	Hatch Combing	4 to 5 mm
P-5	***Peralta***	Deck	5 to 19 mm
P-8	***Peralta***	Column	25 to 30 mm
E-1	***Emile Vidal***	Deck	Less than 1 mm [3]
E-4	***Emile Vidal***	Hatch Combing	Less than 1 mm
A-1	***Armand Concidere***	Deck	Less than 1 mm
A-6	***Armand Concidere***	Hatch Combing	Less than 1 mm
A-8	***Armand Concidere***	Hull	Less than 1 mm
Y-1	***Yogn***	Hull	Less than 1 mm
Y-6	***Yogn***	Hull	Less than 1 mm

1 Measured from exterior end of core
2 Carbonation also evident along longitudinal crack
3 Carbonation also evident along transverse plane of spalling

Table 2a
Compressive Strength of Cores Extracted
From Hulls of Powell River Ships (1998 study)

Core No.	Ship	Structure	Compressive Strength[1]
A-10	***Armand Concidere***	Hull	51.6 MPa (7480 psi)
Y-7	***Yogn***	Hull	60.0 MPa (8700 psi)
Y-8	***Yogn***	Hull	53.8 MPa (7810 psi)

1 Cores tested saturated, surface dry (SSD) per ASTM C 42

Table 2b
Compressive Strength of Other Cores Extracted
From Powell River Ships (1998 Study)

Core No.	**Ship**	**Structure**	**Compressive Strength**[2]
P-3	***Peralta***	Hatch Combing	34.5 MPa (5000 psi)
P-8	***Peralta***	Column	34.3 MPa (4970 psi)
E-4	***Emile Vidal***	Hatch Combing	44.5 MPa (6450 psi)
A-2	***Armand Concidere***	Deck	39.1 MPa (5670 psi)

2 Cores tested, as received, per ASTM C 42

Fig. 1 Aerial view of the ten concrete ships at the Powell River site. (Photograph compliments of Tom Holm, Expanded Shale Clay and Slate Institute).

Fig. 2 Composite image of (clockwise from top left) the *Peralta*, *Emile Vidal*, *Armand Concidere*, and *Yogn*.

Fig. 3 Severe spalling along the hull of the *Emile Vidal* exposes corroded steel reinforcement. Most of the surface distress on the other ships built in the 1940's is not so severe.

Fig. 4 Photograph shows steel reinforcing bars exposed by coring along the hull of the *Yogn* are in good condition with negligible corrosion.

Fig. 5 Longitudinally cross sections of a core drilled over a diagonal crack along the hull of the *Armand Concidere* shows no corrosion of steel and minimal carbonation of paste. The lower section was treated with phenolphthalein.

Fig. 6 View of the interior of a cabin on the *Emile Vidal* shows minimal deterioration of surfaces protected from rain and seawater.

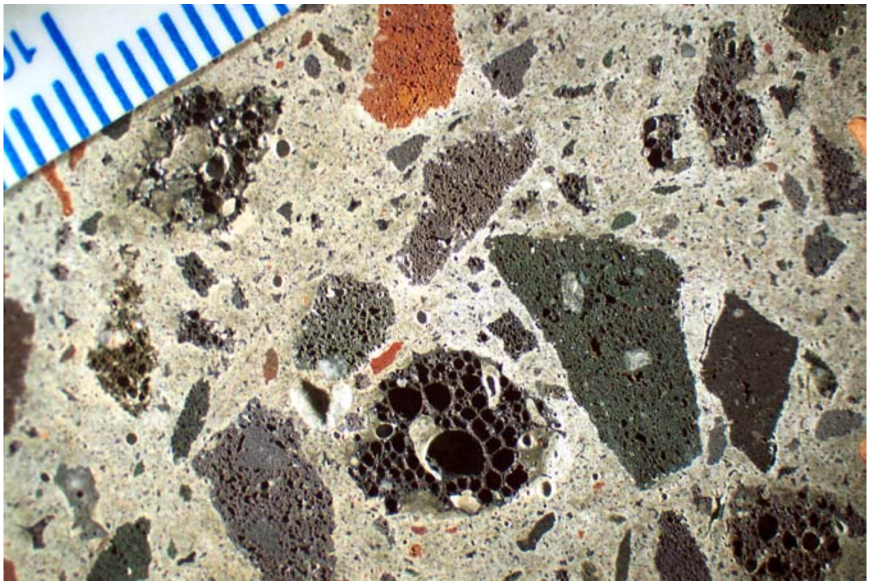


Fig. 7 Finely-ground cross section of a concrete sample taken from the *Peralta* shows the appearance of the manufactured lightweight aggregate and good condition of the cement matrix. Millimeter scale shown.

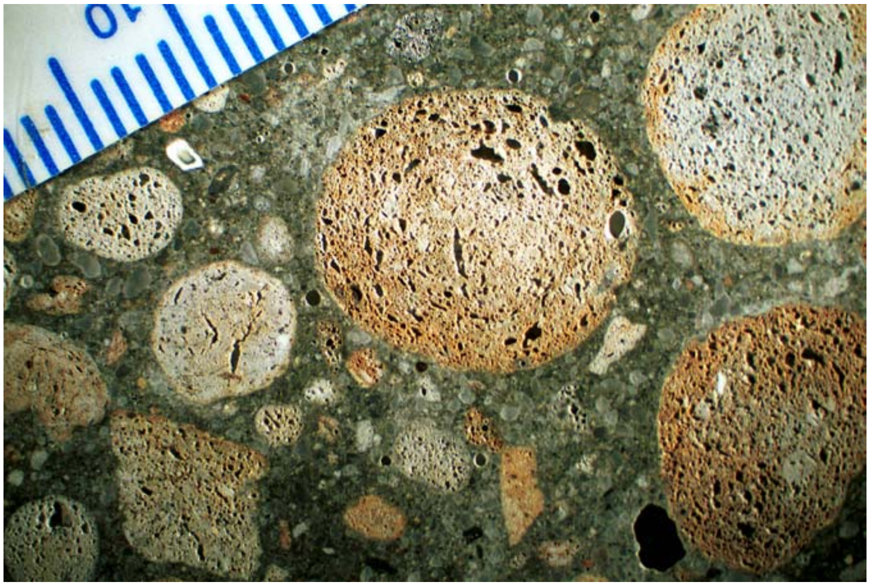


Fig. 8 Finely-ground cross section of a concrete sample taken from the *Armand Concidere* shows the appearance and condition of the cement paste and manufactured aggregate. Millimeter scale.

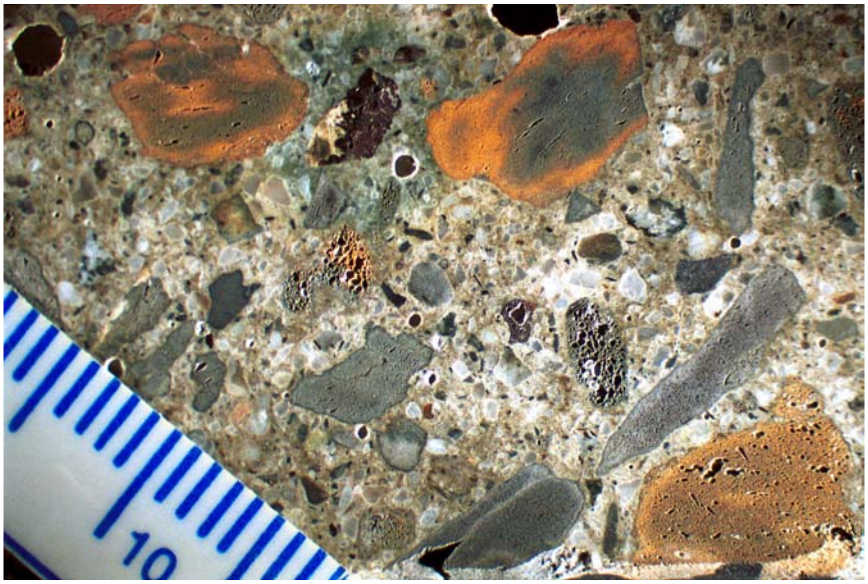


Fig. 9 Finely-ground cross section of concrete taken from the *Yogn*. Lightweight coarse aggregate and natural sand were used in the concrete. Millimeter scale shown.

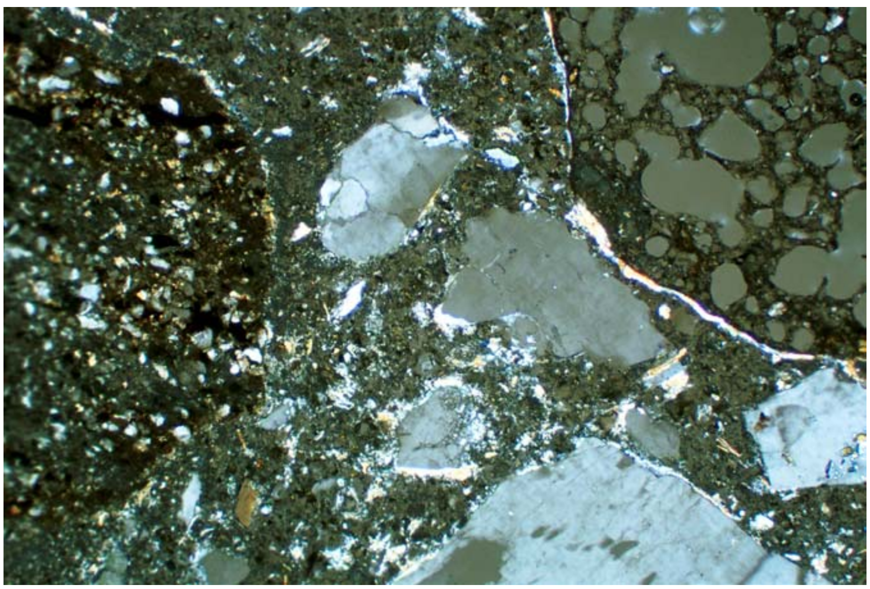
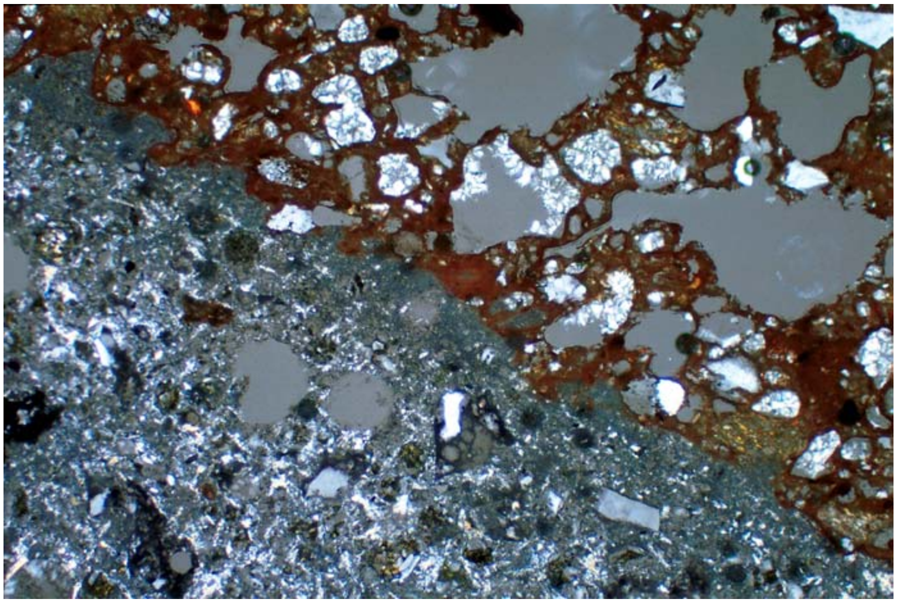
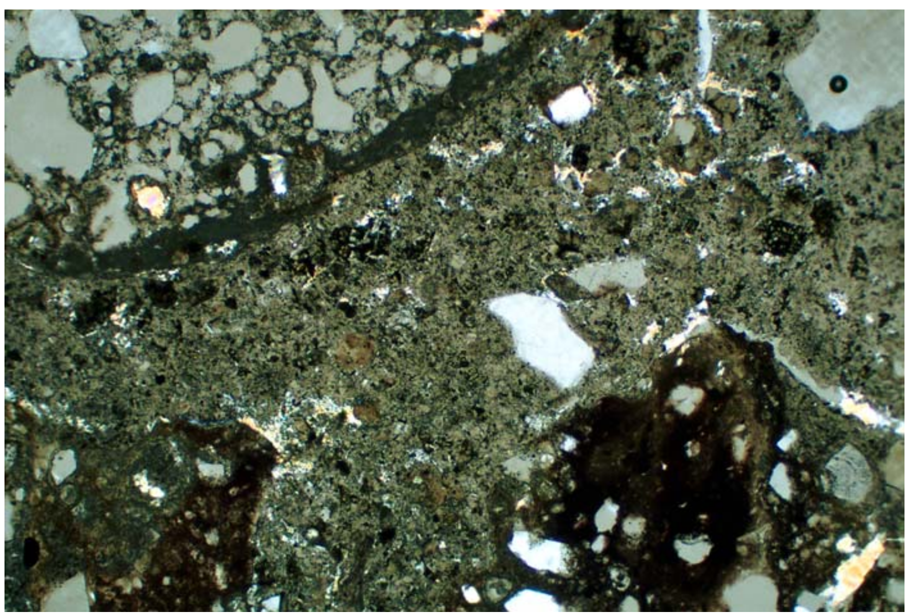


Fig. 10 Thin section photomicrograph showing portlandite crystals filling gaps along the periphery of aggregates (marked with arrows) in concrete from the *Yogn*. Polarized light. Length of field = 1.3 mm.



Peralta



Armand Concidere

Fig. 11 Thin section photomicrographs of concrete from the *Peralta* and *Armand Concidere* showing evidence of non-deleterious paste-aggregate reaction (marked between arrows). Polarized light. Length of each field = 1.3 mm.