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High Performance Lightweight Concrete — A Review

by T. W. Bremner and T. A. Holm

Synopsis: The intrinsic nature of lightweight concrete is to produce a material which, in addition to having high strength, can also have high performance in severe service conditions. The reason for high performance is examined in light of physical, chemical and mechanical properties of the vesicular aggregate used to produce lightweight concrete. The manufacturing process usually involves heating the aggregate to 1200°C which, in addition to rendering it more stable than conventional aggregates when concretes made from it are exposed to fire, also results in a less stiff aggregate inclusion that more closely matches the stiffness of the cement paste matrix. The use of less stiff aggregates results in a reduction in internal stress concentrations in the concrete which in turn leads to reduced mircocracking. The role that this plays in enhancing the performance of this type of concrete is discussed. The special nature of lightweight concrete provides opportunities for design professionals, and recommendations on how best to achieve high performance concrete using lightweight aggregate are provided.

Keywords: Aggregates; density (mass/volume); fire resistance; high-performance concretes; history; lightweight concretes; manufacturing; strength; thermal resistance

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INTRODUCTION

The current use of the phrase "High Performance Concrete" (HPC) produces a surprisingly uniform image in the minds of practitioners in the English speaking world. It is usually but not exclusively restricted to high strength applications that necessitate water to binder ratios near that required for the chemical reaction between cement and water to go to completion when concrete is moist cured for a relatively long time (1,2).

Concomitant with this high strength and low W/B, is enhanced impermeability to aggressive gases and fluids. The net effect is to render HPC structures significantly less vulnerable to the distress exhibited by existing concrete structures in the public domain. In this connotation it appears to current practitioners to be <u>new</u> and of <u>vital importance</u> even though the words "high" and "performance" as defined by most dictionaries do not individually or collectively give that impression.

Dictionaries and Thesauruses fail to define "high performance", however the definition of the two words collectively in the context of concrete technology conveys the following:

> High Performance Concrete: concrete that has enhanced performance and functional characteristics for a designated application.

This definition will be used to further define "High Performance Lightweight Concrete" (HPLC) where high strength and durability, although of importance, might not always be as great a concern as with normal weight concrete (NC). In this context, high performance might refer to enhanced insulating properties and fire resistance as well as to reduced density. All aspects that are derived from the intrinsic nature of lightweight concrete (LC) and that are not new and are not the result of recent development do not preclude it from being High Performance.

What is new and purported to be better does not always stand the test of time. However, with lightweight concrete most of the desirable properties associated with High Performance have an excellent track record. To instill confidence in its use, the history of lightweight concrete will be reviewed as it relates to these attributes.

This discussion will be restricted to lightweight aggregate concrete, i.e. those concretes in which some or all of the aggregate inclusions are of a vesicular nature with vesicular being defined as containing, composed of, or characterized by having small cavities in a mineral or rock (3). Low density concretes which achieve their low density from the use of entrained air or preformed foam are not included. Although lightweight concrete was formerly defined as concrete having a density of less than 1850 kg/m^3 (115 pcf) and compressive strength of 17.2 MPa (2500 psi) this restriction is not usually imposed (4). The essential part is that it contain at least some aggregates that are of a vesicular nature, and that a concrete of reduced density as compared to normal weight concrete is produced.

Based on the foregoing, the following definition of High Performance Lightweight Concrete (HPLC) is offered:

> High Performance Lightweight Concrete: High Performance concrete that contains aggregates in which some or all are of a vesicular nature.

As with HPC, it is essential that a satisfactory workability be achieved at the time of placing and this usually requires the use of a superplasticizer. Depending on the application, silica fume, fly ash, ground granulated blast furnace slag cement and retarders may be desirable, however they are not essential (1).

GENESIS AND PAST PERFORMANCE OF HPLC

Port of Cosa: Long Term Durability

In the year 273BC, Roman engineers constructed five concrete piers reaching out into the Mediterranean on the West coast of Italy a few kilometres north of where the Tiber empties (5). These piers which are approximately 7 m wide x 10 m long x 5 m high served as a breakwater for the thriving fishing and manufacturing town of Cosa. That they exist to this day is a testament to the skill and knowledge of those ancient builders whose prior experience had taught them to travel large distances to get the essential ingredients to make HPLC. In addition to using a pozzolana from Possuoli, which is a distance of several hundred kilometres from Cosa, they used volcanic tuff - a natural volcanic lightweight aggregate from the Volsinian complex some 60 to 80 km northeast of Cosa. The piers, continuously submerged in salt water and with significant abrasion being caused by lateral drift of beach sands and gravel, have had their dimensions reduced by a surprisingly small amount which indicates that this construction will be around for many more millennia. Of particular importance to modern concrete engineers is that this concrete contained manufactured aggregates. One of the local industries in Cosa was an amphora plant where they fired two-handled clay containers that were used to ship wine around the known world. Broken pieces of amphora were incorporated into the concrete mix in a reasonably systematic way indicating that it was part of the mixture proportions.

Those fired clay pieces differ from those produced in a modern rotary kiln producing expanded clay aggregates in the degree of expansion developed by differing firing temperature regimes. Both expansion processes would normally use essentially the same maximum temperature. With brick manufacture, if the clay is heated too fast a vesicular expanded dimension brick not suitable for masonry construction is produced. It took almost two millennia before a materials pioneer in Kansas, USA recognized the potential of this supposedly inappropriate material. The suitability and long term stability of vitrified clay in concrete construction is verified by the success of this work which should be reassuring to modern engineers. Also, knowing of this good performance would have been of particular interest to the founder of the rotary kiln expanded shale industry some eight decades ago, for no doubt this question was raised when his product was first put on the market.

Pantheon: High Structural Efficiency

Roman engineers established a level of construction of public building that was not surpassed for 1500 years. This era of high profile construction started about 300 BC and was essentially completed by 270 AD, establishing standards of quality that following generations were unable to duplicate let alone advance. The best example of their work is probably the still functional Pantheon with its lightweight concrete dome of 43.3 m diameter which stands as a testament to their understanding of structural design and materials utilization (6). At Hadrian's direction, the builder formed the dome with its panelled recesses from wood and then cast concrete over it. The grain of the wood remains imprinted in the concrete to this day. The bare exposed concrete was covered with lead sheeting until the fifteenth century when it was stripped off to cover a building in the Vatican. The lightweight concrete dome roof with no waterproof layer appears admirably suited to this application with no sign of deterioration or leaking taking place. Of particular importance is that the density of the concrete decreased as they moved up the dome with the tension ring in the bottom being of higher density than the top where essentially only compressive stresses were involved. To achieve this gradation in concrete density the inherent variability of natural lightweight aggregate deposits was used to good advantage. The deposit was apparently selectively mined to extract aggregates of the prescribed densities, a process not compatible with modern mining methods. Modern engineers usually cannot cope with a wide variation in material properties and, as a result, the manufacture of lightweight aggregate by the rotary kiln method came about so that density could be closely controlled.

Armenia: Reduced Seismic Inertial Forces

No country seems to be as well supplied with natural vesicular aggregates as Armenia and they have a long history of using it as the aggregate of choice for concrete construction mainly because they must look to quarried aggregates rather than to alluvial deposits and vesicular aggregates are the easiest to quarry. In the 1870's, Armenian engineers had recognized the need for further research on this material. Their building research institute at Erevan has provided a continuous record of conducting research on natural lightweight aggregates to this day. Being in an earthquake region, they learned early the advantages of reducing the density of the concrete so as to reduce the mass of the structure and thereby reduce lateral forces. The wide variation of aggregates available also enabled them to come up with multicolored decorative panels for the exteriors of their buildings. Because these panels required steel reinforcing, research starting in the 1950's was conducted on this type of construction to evaluate the corrosion potential of steel in lightweight concrete made from volcanically expanded aggregates. These findings were incorporated into the Soviet Union's building code for panelised construction using exposed natural lightweight aggregates.

Manufacturer of Vesicular Structural Grade Aggregates

Large areas of the western United States share a similar geology to Sicily, the Sakhalin Island Region of Russia, Armenia and other volcanic regions in that they are well supplied with natural vesicular aggregates. These aggregates enable moderate strength concrete to be produced that has high performance thermal and fire resisting properties as well as good strength to weight ratios. Achieving higher performance with these materials unfortunately may not be possible because of the inherent wide variability of the natural deposits in terms of degree of expansion and non uniform vesicular diameter which limits its use.

To overcome these disadvantages and to produce a more functionally useful product Mr. Stephen J. Hayde patented in 1917 a method of manufacturing expanded shale aggregate using a rotary kiln. This patent formed the basis for the subsequent wide spread production of lightweight aggregate, that enabled concrete of significantly higher quality to be produced, and dramatically changed building practice. The intrinsic advantage of a uniformly expanded vesicular aggregate that was available in the size factions necessary for the production of high structural efficient concrete was quickly recognized by engineers (7).

Ships Built During World War I: High Durability, Low Cracking

Prior to World War I, concrete ships had been built and proved functional and durable. The first concrete boat reinforced with steel was a small rowboat built by Lambot in 1848; one of his two row boats is on display in the museum at Brignoles in the south of France, the other is in storage at the Musée d'Orsay in Paris. These concrete row boats, though functional, served no commercial role. In World War I, the U.S. Marine Commission, charged with finding an alternative to the steel ships, found that only structural grade lightweight concrete could be a viable material. Initial construction experience showed that only a rotary kiln produced aggregate with high cement content concrete incorporating chemical admixtures could meet their needs. Just such a ship, the U.S.S. Selma, was launched in June 1919. This ship although subject to various marine disasters such as being run aground on a stone sea wall while fully loaded with oil, had a satisfactory service record and, when inspected in 1953 and again in 1988, the concrete was found to be in exceptionally good condition. This is in marked contrast to the Selma's predecessor, the USS Atlantis that was launched some nine months previous. The Atlantis was made of relatively low strength concrete (20-30 MPa) and with a lower quality aggregate made in a bee hive kiln rather than in a rotary kiln. The Selma's rotary kiln produced aggregate, plus enhanced concrete strength (50 MPa) as well as special attention paid to the consistency of the concrete (the "slump cone" was developed and first used during the construction of the Selma) resulted in an advancement in technology equal to what is now being claimed for HPC in concrete bridge deck construction (8).

Bridges and Buildings in the US: High Durability, High Structural Efficiency

The lightweight concrete industry benefited immensely from the research done by the U.S. Marine Commission, and at the end of the war, the design procedures and construction practices developed by the Commission were adopted by industry. In 1922, the Westport High School in Kansas City become the first lightweight structure built with concrete using rotary kiln aggregates and demonstrated the favourable cost and construction reliability of the product.

Factors found effective for producing durable ships were also incorporated in concrete bridge design. By 1935 over 34 lightweight concrete bridges were built in North America including nine in Canada (9). The fact that chemical admixtures that also sometimes entrained air were found desirable in placing lightweight concrete may, in part, account for the good long term performance of many lightweight concrete bridges built in regions where deicing agents are frequently applied. Deicing agents induce deterioration from both increased cycles of freezing and thawing, which the entrained air had a beneficial effect upon and from corrosion of the steel reinforcement, The corrosion is enhanced by the chloride based deicing agents acting as depassivating agents when the chloride ions have diffused into the concrete to the depth of the steel reinforcement. Various factors associated with lightweight concrete tend to reduce the seriousness of this effect and contribute to High Performance. This will be discussed later.

Ships Built During World War II, High Serviceability

The 14 World War I lightweight concrete ships were largely experimental, nevertheless, they were successful with one ship still currently in use in Powell River in British Columbia, Canada. When the same acute shortage of steel plate and surplus reinforcing bars developed at the start of World War II, the U.S. Government built 104 concrete ships, of which 24 were large sea-going vessels and 80 were sea-going barges. All reports indicated good handling and good performance, and they proved sufficiently water tight in service that they could be used to carry and store sugar and wheat. Additionally they were superior to steel in that they experienced minimum sweating and as a result, dry goods did not mould or cake (7).

As in the first world war, all ships built during war time were found unsuitable for peace time use. The steel ships were broken up for scrap and the concrete ships were usually used for piers and breakwaters. The authors have visited many of these ships in the last decade and have found them all in essentially good condition considering the use to which they have been put.

Approximately 10 World War II cargo vessels can be seen near Cape Charles in Virginia where they serve as a breakwater for a now abandoned ferry terminal. All ships were sunk and then filled full of sand. The nature of the loading and the undermining of the bows and sterns by the current has caused most of them to break amidships however this is not unexpected. The only significant area of distress in these ships and in the USS Selma is in the thin, highly reinforced decks where improper concrete placing procedures appear to be the main cause of the problems. The hulls, where not damaged by very hard berthing or from overloading, are generally in excellent condition. The condition of all of the ships surveyed conveys confidence in the state of the art some 55 years ago. With the lessons learned from close examination of these ships, good long term performance for lightweight concrete ships today is certainly achievable.

Rotary Kiln Expanded Aggregate Experience In The Former Soviet Union: High Thermal Resistance

The early 1950's saw the Soviet Unions' commitment to make housing available to the Soviet people in the form of industrially produced precast concrete panels to form multi-storey apartment buildings. It was essential that the panels for the exterior walls be both load bearing and have high thermal insulating properties and be composed of fire resistant materials. The use of rotary kiln produced expanded clay (keramzite) concrete was found ideally suited for making the panels in all climatic regions in the former USSR. While most panels were made with monolithic lightweight concrete of high thermal resistance, in some cases a sandwich panel type of construction was used with high strength lightweight concrete skins about 75 mm thick being separated by a highly insulating concrete core. The skins had a density of about 1800 kg/m^3 and the core had a density of about 1200 kg/m^3 (10). To implement this type of construction in a country where only local areas such as Armenia had experience with lightweight concrete required the establishment of a research institute to investigate and come up with designs not only for the buildings and the building components but for the infrastructure to build them as well. This work needed to include everything from the economical production of aggregates from suitable clay sources near population centres to the finished building. To accomplish this, starting in 1950, a group of about 100 scientists and engineers worked at a special research institute in Samara (formerly Kuybyshev). These people provided the designs and guidance that enabled great strides to be made in housing the nation. An important consideration was that combustible materials and materials generating noxious gases should not be incorporated in the building.

For four decades this talented team of highly qualified specialists worked to achieve optimum performance in the material used for the exterior panels. The extremely functional material developed - High Performance Lightweight Concrete - has yet to be fully appreciated by their current government or by the West.

Offshore Structures: High Durability, High Specific Strength

Oil production in the offshore requires either fixed or floating platforms and, given the success of the lightweight concrete ships in World War I and II, it is not surprising that the oil industry turned to structural grade lightweight concrete. Prior to embarking on this work a group of eleven companies funded a joint industrial study to investigate the use of high strength lightweight aggregate concrete for Arctic applications. The results have wide applicability as the effect of typical construction scenarios were incorporated into the testing program. Such design parameters as modulus of elasticity, splitting tensile strength and thermal properties were evaluated and fully reported for high strength concrete, areas which previously were not well defined (11). The net effect of this multi-million dollar research program is that now, high performance high strength lightweight concrete is as well defined in the technical literature as normal weight concrete. Given the large number of aggregate types and the even larger number of aggregate suppliers world wide, it is unlikely that all the natural aggregates being used in concrete will ever be defined as closely as this multi-national research group did for lightweight.

As part of their on-going research program on concrete for offshore construction, CANMET carried out an extensive testing program to develop high strength concrete using a Canadian lightweight aggregate. This work established that 70 MPa concrete with a density of 2000 kg/m^3 could be produced commercially and that it would have freezing and thawing resistance suitable for cold northern waters (12).

With over 70 years experience with lightweight concrete ships and over 40 years experience with lightweight concrete barges and platforms along the coast of the Gulf of Mexico, it was natural for the oil industry to select lightweight concrete for the Tarsuit and Super CIDS that were installed in the Beaufort Sea. To gain experience with placing of lightweight concrete mixtures for high strength application, Norwegian Contractors slipformed part of a leaning tower at their Stravanger Yard using German lightweight aggregated in lightweight concrete and slipformed lightweight concrete shafts containing US lightweight aggregates in Corpus Christi, Texas in both winter and summer to demonstrate the practicality of both the material and the construction method. Based on this experience they and others have used lightweight concrete successfully in many applications in the North Sea involving floating and fixed facilities for the oil industry as well as for pontoons for two floating bridges (13).

NATURE OF HPLC

Lightweight Aggregates as Vesicular Inclusions

During the high temperature production of either natural or manufactured lightweight aggregates there is a partial decomposition of some of the compounds within the aggregate mass takes place. This decomposition results in the release of gases which coalesce to form vesicules or cells within the aggregate mass. This expanded or distended form is retained upon cooling and accounts for the aggregate being light weight. The nature of the rock must be such that it has a reasonably wide bloating range and will remain sufficiently viscous at high temperature to retain the gas bubbles. As with foam plastics. the object is to develop a closed cell foam structure and to avoid producing an excessively expanded open type cell system.

The closed cell foam is characterized by being rigid with low water permeability. With an open cell foam, a flexible and highly permeable material results. Unlike cellular plastics, the vesicules in aggregates are formed at very high temperature and upon cooling the gases contract inside the pores with the result that with a normal degree of expansion there appears to be some connectivity between individual pores. These conduits are not easily seen in a scanning electron microscope even at magnifications in excess of 3000 indicating that if there are pores, they either self-seal at high temperature or are of dimensions less than 30 nm (14).

Most lightweight aggregates have a silica rich vitreous ceramic like matrix surrounding the vesicules that will be resistant to fluid flow. Evidence to support the limited connectivity of all internal pores is the fact that the aggregates will not normally become fully saturated if stored under water for several years. Most aggregates have a rapid absorption rate in the first 30 minutes that precludes the use of air dry or oven dry aggregates in concrete mixtures. If submerged in water for 24 hours (24 hour absorption test), the subsequent rate of water absorption is so low as to have a negligible