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Production, Construction and Quality Control of High Performance LWA Concrete for Marine and Other Severe Exposure Environments

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Abstract

Lightweight Aggregate (LWA) is commonly used to reduce the weight of concrete structures. The differences in mechanical and physical characteristics between Normal Weight Aggregate (NWA) and Lightweight Aggregate (LWA) are substantial, and become more pronounced as the materials are being utilized closer to their physical limitations. This paper highlights some of the practical challenges of using LWA in high performance concrete in marine environments, and presents some of the experiences gained from the Hibernia Offshore Concrete Platform, at present being built in Atlantic Canada. This structure will use a blend of NW and LW Aggregates to modify the density of an 80 MPa cylinder strength concrete in order to improve the buoyancy of the structure. Results from both the pre-construction trials and the introduction verifications indicate that this Modified Normal Density (MND) concrete can be produced and placed to a high quality level using ordinary construction equipment and procedures.

Introduction

The use of Lightweight Aggregate to reduce concrete densities is a well established procedure where ease of handling or reduced foundation loads is a premium, and concrete with compressive strength in the region of 10 to 40 MPa cylinder strength is routinely made. In later developments, LW Aggregates have been used in High Strength concrete to improve buoyancy for permanent or temporary floating oil platforms in Europe and North America (Hoff et. Al., 1995).

High Strength (more than 50 MPa cylinder compressive strength) concrete relies more heavily on the quality of the aggregates than low or even medium strength concrete, where the function of the aggregate to a large extent is to act as a cheap filler material, and most of the load is taken up by the mortar matrix. As design loads approach and exceed the strength limits of the mortar matrix, as is often the case with High Strength concrete, the load carrying capacity of the aggregate and the interplay between aggregate and matrix become the limiting factors in strength development. For all practical purposes, this limit appears to be in the region of 100 to 110 MPa (compressive cylinder strength) for concrete using normal weight aggregate, and probably is less than 70% of this for LWA for normal mix proportions. For lightweight concrete this limitation is even more pronounced, because the mechanical characteristics of the LW aggregate are more similar to those of the mortar matrix than the NW aggregate, and variations in aggregate quality will more directly be reflected in the concrete characteristics. Aggregates normally constitute 60-70% of a concrete mix, and the porosity, density and physical structure of the aggregate will therefore have a profound influence on the physical property of the concrete.

LWA Materials for High Strength Concrete

An ideal LWA material would have the following characteristics:

- High material density to provide mechanical strength
- High porosity to give low particle density
- Sealed surface to reduce absorption

No such material is commercially available, and production of LWA concrete will therefore have to be a compromise between requirements based on material limitations and the contractors'' ability to manipulate materials, equipment and processes in order to satisfy these requirements. A "best fit" scenario will often turn out to be the final answer.

The single most influential characteristic of the LWA material is its great porosity, affecting not only density, but also the mechanical strength and durability of the hardened concrete, as well as the fresh concrete characteristics. This porosity makes the aggregate mechanically weak and crushing and breakage during storage and handling can alter the particle grading sufficient to reduce the fineness modulus (FM). This can result in an increased water demand for the concrete, as well as increasing the absorbability of the aggregates as more pores are exposed at the fracture zone.

The porosity of the LWA material poses another practical problem during storage and batching. A dry aggregate can easily absorb moisture from the surroundings, making the density control of the concrete very difficult. Moisture absorbed during and after batching can only come from the mix water, resulting in slump loss and reduced workability. The effect of admixtures will also vary as these chemicals are absorbed into the LW aggregate leaving less quantities to act on the concrete mix.

The selection of LWA material is therefore one of the more important decisions in the overall process of producing LWA containing structures. Once the material is selected and characteristics are established, concrete production will have to be modified to suit the material. Alternatively, when production process and equipment are established, the choice of LWA materials becomes very limited, and will have to fit within the framework set by production. This can be illustrated by the very different approach to proportion philosophy and LWA material and placing equipment selected by two different projects to solve the same basic problem (Table 1).

The Norwegian Troll and the Canadian Hibernia are both Gravity Base Structures (GBS), off shore concrete platforms, to be permanently installed on the seabed during operation. As part of the production and installation process, however, these structures will require buoyancy while in a floating mode. During the early stage of construction, a requirement for improved buoyancy developed for both structures, and a reduction in concrete density by the use of LWA was independently selected.

The general requirement for developing a High Strength Lightweight Concrete is the same as for any other concrete, namely to design a material that can be produced, transported and placed efficiently, consistently and safely, to meet the required in place quality.

In addition, because of the high reinforcement density of the Hibernia structure, in extreme cases of more than 2000 kg/m^3, the concrete was required to have extreme flowability, high slump, good homogeneity and excellent stability when placed and compacted. Because of the initial selection of pumping as a means of placement, and in order to maintain slump and workability during transport and compaction, a tight moisture control was required to ensure that the material is fully saturated during batching. Slip forming as a production method is demanding, because after the first batch of concrete is placed into the form, the process is in motion, and it is the setting time of the concrete, rather than material logistics or productivity, that control the pace of construction.

For the Troll Platform, the proportion philosophy was to maintain the same mechanical characteristics as in the original Normal Weight concrete is replaced, and to use LWA to reduce the concrete density. This resulted in a complete re-design of the concrete, as the granitic NW aggregate had to be replaced with a denser and much stiffer quartz-diorite aggregate in order for the combined E-modulus of the concrete to remain the same as in the unmodified concrete. Because of the relatively high particle density of the selected LWA material, a European expanded clay product (Leca 800) with high absorption (Table 2), the LWA material had to be maintained and batched in a dry state and pumping as a means of placing concrete was no longer deemed possible. All concrete had to be placed using a sophisticated system of conveyer belts, and the aggregate had to be stockpiled in a protected environment with full moisture and temperature control. Rebatching with addition of super plasticizers also had to be arranged due to slump loss during conveying.

For the Hibernia Platform, we chose to follow a different path both to save time and to be able to utilize batching and placing equipment all ready available at the Bull Arm Site, together with cement and NW aggregate currently in use at the project.

Material Selection Process

The design for the Hibernia GBS was already far advanced and construction was in progress, and a time constraint therefore existed for developing, testing and documenting an MND concrete that would meet the design criteria with acceptable margins, and at the same time would result in the desired reduction in density.

Given that some degree of freedom always exists within the framework of the criteria put forth by the designers, by exploiting the allowable slack, materials as different as NW and LW aggregates can be combined in a manner that would give the desired reduction in concrete density and still meet the design criteria as established (Table 3-Design Criteria for NW and MND Concrete). Due to time constraints, a LWA material that could be handled, stored, batched and compacted in a manner similar to a normal weight aggregate was the target. This always required a LWA material that could be kept in a state of total saturation in order to facilitate concrete pumping as the preferred method of placing concrete. The resulting material had to provide a combination of low density, low absorption and high strength.

Fortunately, a lot of work had been done by Dr. G. Hoff's group at Mobil Research and Development Corp. in Dallas, TX, as part of the Hibernia owner consortium HMDC (G.C. Hoff et. al., 1992). The group had established basic physical and mechanical characteristics of both relevant LWA materials, and of several types of LWA concrete. This work indicated very clearly that suitable material could be found in North American based on expanded shale, rather than expanded clay as had most commonly been used to produce high strength lightweight concrete (Table 3). The Hibernia Project could therefore skip the time-consuming operation of screening a wide variety of LWA materials, and instead concentrate on a selected few.

A quality plan (Table 4) established for the MND concrete development turned out to be quiet effective and provided the project with both a yard stick to measure progress, and a continuous verification system, allowing construction planning to proceed while material development was still in progress.

A parallel testing procedure was set up at the Bull Arm Construction site, where a CSA certified concrete laboratory was established to provide QC testing and documentation. Two North American LWA materials, "Solite" from Solite Company at Mount Marion, NY, and "Stalite" from Carolina Stalite Company in Gold Hill, NC were compared in a mix configuration proportioned to meet the established design criteria (Table 5). A well-known LWA material (Liapor of Germany), with several references from offshore applications in Europe, was used as a reference.

As expected, the E-Modulus turned out to be the mechanical parameter most difficult to maintain when NW aggregate was displaced with LW aggregate (Table 6). The E-Modulus of the resulting MND concrete was therefore, together with density, used as the final criteria for selecting the LWA aggregate to be used for the rest of the Hibernia Platform.

Production Challenges

The typical Hibernia concrete (Table 7) contains only 159 kg/m^3 of water. With a high admixture dosage (7.5 kg/m^3) and very high slump (220 mm), there is barely sufficient water available to fully coat all the ingredients, and at the same time develop the properties of the admixtures. It was therefore a concern that slump loss and rapid reduction in workability might develop, if the LWA material was not fully saturated or if pump pressure peaked during blockage or after a prolonged stop. The great difference in density between LW (1550 kg/m^3) and NW (2650 kg/m^3) aggregates, together with heavy vibration, was likewise envisioned to cause separation in a high slump concrete like that one used at Hibernia.

By looking into the individual densities of the major parts of a fresh concrete mix (aggregates and the cement/water paste), it becomes apparent that the relative difference between the density of the paste and the LWA is approximately the same as between the paste and the NWA (Table 8). Hence, material separation should not be a major problem, if the mix is fairly well proportioned and homogeneously mixed.

In order to investigate this concern, 150 300 mm cylinders with both NW and MND concrete were cast using concrete with slump of more than 240 mm. The cylinders were placed on a vibration table and heavily vibrated for 5 minutes without smoothing or finishing the surface. After sufficient curing the cylinders were split along the long axis, and aggregate distribution was visually examined. The results (graphically presented in Figure 1) indicate that the MND concrete is as homogeneous, or even more so, than the NW concrete, where the coarse aggregate has a tendency to sink downwards. This "separation" is somewhat less pronounced in the MND concrete, probably because the LWA, though less dense than the paste, is still more similar to the paste than the NWA, and so helps to stabilize the entire mixture. The rough surface often observed with concrete containing LWA is more a result of the paste "flowing down" from the LWA grains than a sign of separation.

Investigation into a possible pumping problem was much more elaborate. A full scale pump test was performed, using a modified test rig prior to establishing the final mix design (Figure 2). The rig consisted of a 5000 kW piston pump connected to a 15 m section of a 5-inch pipeline. The pipeline was fitted with a guillotine valve and a pressure gauge at the blank end and a gauge at the pump end to monitor pressure drop along the line. Pump pressure was recorded from the hydraulic system at the pump.

Standard production concrete was tested for slump and air was pumped through the rig at normal pumping speeds. The valve was then closed for 5 minutes, while maximum pump pressure was maintained. After resuming normal pumping, concrete in the pumpline was again tested for slump, flowability and air content (Table 9).

During normal production pumping, a high pressure situation like this will usually occur as a result of blockage of pumplines, and the pressure is normally relieved immediately by the operator. A maximum pressure situation over a time span of 5 minutes is considered to be extreme, and it was thought that if the reduction in slump and workability was acceptable after this treatment, there was no hesitation to use the concrete in production. This turned out to be correct, and the same procedure, using a similar pump set up, was successfully used to qualify other mix designs later in the project.

Summary

At this point in time, approximately 75,000 m^3 of MND concrete have been placed at the project, through some very demanding climatic conditions with high wind, freezing rain, and sub-zero winter temperatures. The MND concrete has turned out to be extremely resilient, stable and forgiving, in spite of complex geometry and extreme reinforcement density (Table 10). This is encouraging for concrete for marine and other severe environmental applications

References

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