Materials for high density concrete production

High density concrete can only be manufactured by using various high density natural or man-made aggregates. High density concrete can be used for structural and/or specialised construction purposes. The main use of HDC is in the nuclear industry as radiation shielding. Special care should be taken to the specific type of aggregates used and type of cements combined in the concrete mix.

High density concrete (HDC) consists of concrete with a density higher than normal 2300 to 2550 kg/m³ and is used for special purposes such as radiation shielding, counter weights, ballasts, safe walls and safe roofs.

The aim and objective of this assignment is to:

- Outline the constituent materials required for high density concrete.
- Outline the production, placing and compaction procedures for high density concrete.
- Outline the quality control procedures required for high density concrete.
- Discuss an application for high density concrete and highlighting any problems encountered.

3. Constituent materials for high density concrete.

All constitute materials, cement, admixtures, and water used in high density concrete should conform to the standards as for normal density concrete, but the aggregates is different and may require special consideration during handling, batching, mixing, transporting and placing. (ACI 304R-00, 2000)

3. 1 Aggregates.

High density concrete (HDC), densities is achieved by using high-density aggregates usually iron oxides and depends on its intended use, physical and chemical properties, availability and cost. Concrete densities of 3700 to 3800 kg/m³, is obtainable utilizing aggregates with particle relative densities of at least 4500 kg/m³ and for concrete densities of 4800 kg/m³ aggregates should have a particle relative density of at least 6000 kg/m³. (J. Goodman, 2009)

Aggregate grading for HDC rarely conform to normal aggregate standards as the aggregate are rarely made for concrete production, this should be accepted by potential users as it is not detrimental to the production of HDC. The most important part of HDC aggregates is that the grading should be constant and that a workable grading limit be agreed on with the supplier, to base the mix design on.

The chemical properties of all high-density aggregates should be evaluated before use, chemical reactivity and particularly in high alkaline environments as found in cement pastes, long term durability such as alkali-aggregate reactivity, sulphate and chloride attack and other impurities. The supplier should be able to provide a full chemical analysis of all potential materials and alternative materials to be used. With proper technical evaluation and planning, different types of aggregates can be combined at the supplier yard to produce a concrete with predicted, specified density. Cost factor are very important as these aggregates are usually more expensive than normal aggregates, it can also be that the material may only be available in relative short supply. The cost of HDC increases with density but not necessary in direct proportion. (E. Miller, 2003)

Aggregates should be selected for their shape (cubical or rounded and free of flat or elongated, maximum density, workability, and cost. Particle relative density of the fine aggregate should be similar to that of the coarse aggregate as lower density fine aggregate can lead to segregation of the coarse aggregate through the mortar. (J. Goodman, 2009)

The grading of the coarse aggregate should be uniformly graded between 10 and 40mm, as per limits in Table 1. The grading of the fine aggregate should be within the limit as shown in Table 1 as this would help to prevent segregation. (ACI 304R-00, 2000)

Sieve sizes mm

Grading 1 for 37. 5 mm maximum size aggregates % passing

Grading 2 for 19. 0 mm maximum size aggregates % passing

Coarse aggregates

Two types of aggregates can be used for high density concrete namely:

Natural occurring aggregates.

Iron ores of various types have been used all around the globe for many years (outside the U. K), in the UK imported iron ore is used. (E. Miller, 2003) Using some natural occurring aggregates concrete densities of approximately 4000 kg/m³ can be obtained. (J. Goodman, 2009)

Different types of natural high-density aggregates which can be used for high density concrete (HDC) available in South Africa and the UK refer to Table 2.

Man-made aggregates.

To achieve concrete densities above 4000 kg/m³ man-made or synthetic material such as ferrosilicon slag, steel or lead shot can be used. (J. Goodman, 2009)

For types of man-made aggregates which can be used for high density concrete (HDC) available in South Africa and the UK refer to Table 2.

3. 2 Cements.

All cements conforming to SANS 50197 as for conventional concrete can be used for HDC if it produces the required physical properties. If alkali-reactive constituents are present in the aggregates cements with low alkali contents or a suitable blend of cements and cement extenders should be used. (J. Goodman, 2009) Low-alkali cement not having more that 0. 6 % Na2O-eq may be used with a potentially alkali-reactive aggregate such as lead shot. (B. Oberholster, 2009)

The following extenders: Ground granulated blast furnace slag (GGBS), fly ash (FA) and Condensed silica fume (CFS) have lower densities than Ordinary Portland Cement (OPC) and can be used if they do not reduce the density of the concrete below specified limits, (J. Goodman, 2009) Eric Miller (2003) however states " The cement can be OPC or a blend of this with either Ground granulated blast furnace slag, Pozzolanic fly ash; the latter which will not reduce the density of the concrete but may enhance the otherwise poor workability”. Fly ash blends and lower water contents can successfully be used to increase the density of concretes. When lad shot is used High alumina cement (HAC) must be used, (J. Goodman, 2009) as it reduces the chemical reactivity of lead in high alkaline conditions. (E. Miller, 2003)

When using alkali-reactive aggregate (lead shot) deleterious expansion can be prevented when using high-alkali cements by adding extenders complying with SANS 1491 by using a minimum percentage of the following extenders by total mass of cement:

At least 40% Slag (S) by mass

At least 15% CSF by mass

At least 20% FA by mass (B. Oberholster, 2009)

Barytes for example tend to have a very coarse grading, the cohesivenesss of the mix can be imoproved by adding additional cementitious material such as PFGA/GGBS. The cementitious content can be higher than required for normal strength or w/c design criteria. Adding additional cementitious material to modify the fines content of the mix may, seem expensive but in HDC it is the cheapest ingredient used and relative easy to include. (E. Miller, 2003)

3. 3 Admixtures.

Adding admixtures can minimise segregation, bleeding, both of which can be problematic with HDC. The durability can be improved with a low free water/cement ratio (w/c) especially so in structural grade HDC. Using super plasticisers is recommended which in conjunction the cement type may marginally increase concrete density. Super plasticisers are beneficial in reducing water to minimise bleeding and maintain a cohesive mix that has minimum segregation. (E. Miller, 2003)

The following admixture can be used in HDC:

Air-entraining admixtures as it controls bleeding and settlement improve workability and assist in obtaining more homogenous concrete but will reduce the density of the concrete. Water-reducing admixtures as it will increase concrete density by reducing the amount of water in the mix, water is the material used in HDC with the lowest density. Shrinkage-reducing admixtures as it ensure dense, crack-free concrete used for radiation-shielding concrete. (J. Goodman, 2009)

When lead shot or lead containing aggregates are to be used, the following should be considered when selecting a chemical admixture. The alkali content of chemical admixtures for concrete used in South Africa is between about 0. 2 and 7%. In many instances the contribution to the alkali content of the pore solution is significant and cannot be ignored. One of the widely used super plasticisers has a Na2O-eq of about 5% and if added at 1% of cement to concrete with a cement content of 350 kg/m^3 it will ad 0. 17 kg/m^3 Na2O-eq to the concrete. Lithium based compounds can be used with lead shot to control the alkali reactivity. (B. Oberholster, 2009)

The effect of admixtures should be established under field conditions, preferably by testing, to determine if the admixtures achieve the required results or totally unsuitability. (J. Goodman, 2009)

Admixtures may only be used in liquid form and batched in solution in the mixing water. Admixtures shall comply with the requirements of ASTM C 94 or AASHTO M I94; air entraining agents shall comply with the requirements of ASTM C 260 or AASHTO M 154. Admixtures shall not contain any chlorides.

(COLTO, 1998)

3. 4 Water.

Water shall be clean and free from detrimental concentrations of acids, alkalis, salts, sugar and other organic or chemical substances that could impair the durability and strength of concrete or imbedded steel. (COLTO, 1998)

4. Production, placing, compaction and quality control of high density concrete.

4. 1. Production.

Standard batching procedures can be used for naturally occurring aggregates such as Barytes and Magnetite with volume modifications to allow for the increase in aggregate relative density. These, and occasionally other types, are sometimes required in significant volumes to justify large-scale batching through conventional plant. It is sometimes necessary to use smaller drum mixers approximately 0. 5m^3 and even smaller for lead shot. (E. Miller, 2003)

Normal batching (if sufficiently accurate) and handling equipment can be used but great care should be taken not to overload the equipment as HDC is much denser. It is imported to clean all equipment used to minimize cross contamination. (J. Goodman, 2009)

To aid production aggregates can be purchased from some suppliers pre-weighted in ' dump sacks' or other containers to suit the size of the batching plant, the additional cost being more than the offset by an almost nil wastage, and providing additional protection from external contamination. Iron or lead shot can also be purchased in 25 and 12. 5 kg bags respectively but this tends to make batching very tedious. The use of dump sacks for supplying relatively small amounts of aggregates has obvious advantages as suppliers have the flexibility to blend precise quantities of fine and coarse aggregates of different types to offer tailor-made premixed all-in blends as well as tailor-made densities.

Batching times will take longer per cubic metre, due to smaller unit batch volumes, but individual batch mixing times should be similar to those for standard aggregates concretes. Care must be taken with Barytes to assess potential particle break down, since this material can be weak and fragile. Conversely mixing times may need to be extended for materials such as Fergran, which has a very rough and irregular shape. It is advisable to pre-grout mixers when small quantities are produced. (E. Miller, 2003)

Special care should be taken to prevent loss of fines, contamination, segregation, aggregate breakage when shipped, handled and stored. The aggregate should be kept as dry as possible. Aggregate container should be marked properly containing the mass and type of the aggregate. (J. Goodman, 2009)

4. 2 Placing.

Conventional placement methods may be used for HDC, provided that the mixture is workable and the forms are relatively free of embedded items. Such concrete, however, presents special problems due to the tendency of the high-density aggregates particles to segregate. Segregation is greatest where the aggregates are not uniform in grading or density, the mixture contains excessive water, or the slump is excessive. The slump for high-density aggregates mixtures should normally be between 40 and 75 mm.

Placement of conventionally mixed HDC is subjected to the same consideration of quality control as normal concrete, except that it is far more susceptible to variations in quality due to improper handling. HDC is particularly subject to segregation which results in variations of strength and density.

HDC will not flow in a form and must be placed in each discrete area and compacted in place with minimum vibration. Under no circumstances should an attempt be made to move HDC with vibration equipment. Concrete should be placed in layers not more that 300 mm thick. If an excessive amount of grout builds up on the surface, it should be removed while the concrete is still in plastic. When segregation cannot be avoided or when embedded items or restrictions prohibit conventional placement, the pre-place aggregate method may be used.

Pre-placed aggregate construction consists of erecting formwork, pre-placing coarse aggregate in the forms, and mixing and placing high-density grout using the same procedure as those employed with normal grout.

Pressures exerted on formwork by HDC are greater than those exerted by normal concrete and formwork must be designed accordingly. Pressure on vertical forms can be reduced by placing concrete in slow rising lifts. (J. Goodman, 2009)

If possible the use of long, rigid chutes or drop pipes should be avoided. If HDC concrete is placed in narrow forms or through restricted areas, it is advisable to use short, flexible drop chutes that can collapse and restrict the fall. (ACI 304R-00, 2000)

4. 3 Compaction.

Compaction is of great importance when using HDC due to the special purposes i. e. radiation shielding it is used for which requires maximum density, and the concrete should be free of segregation and voids. Compacting HDC is more difficult to compact than normal concrete and extra special care should be taken to ensure proper compaction. Both internal vibration and external vibration are used. However care should be taken when using high-density aggregates some are friable and can easily break down. Poker vibrators insert points should be spaced closer to ensure that HDC are compacted properly.

Normal frequencies vibrators as well as high frequency (180 Hz) can be used successfully satisfactory. Higher frequencies vibrators must be used for shorter periods, to reduce the danger of segregation. Over-vibration causes segregation of the high-density aggregates by settlement meaning the large aggregate migrate to the bottom of the element casted. (J. Goodman, 2009)

The area radius of action of vibrators used in HDC is less effective. This result in HDC not being compacted properly and greater care should be exercise to insure proper compaction of the concrete. Excessive grout can be lifted to the lift surface top due to vibration and re-vibration, as to remove entrapped air and establish aggregate-to-aggregate contact. The lift surface grout should be removed while the concrete is still fresh. (ACI 304R-00, 2000)

4. 4 Quality Control.

HDC requires careful planning at design stage, tender assessment and pre-production stages of a contract as well as during actual production on-site. Cost can be very high compared with standard concrete as volumes are often too small to be successfully produced in conventional ready-mixed or site-mixing concrete plants. Workability can be difficult to assess, hence the need for trial mixes which should be attended by site personnel including those actually placing the material. A higher degree of quality control is needed, with fresh densities being frequently measured prior to mixes being placed. This requires appropriate equipment that is not usually on site. Full method statements and quality plans for all stages, including materials procurement, planning, production, placing and testing, should be prepared and approved prior to starting of work.

Because of the need to satisfy special requirements, testing and quality control are extremely important. In many cases, testing of the structure, including the removal of cores is not permissible. Care must be taken to ensure that good concreting techniques are used.

The density of HDC is important, if not more so at times, than strength and a suitable testing regime should be adopted to continually monitor this property using fresh density tests on site before concrete is placed. Cubes and cylinder tests are similar to normal concrete. Generally 100 mm and 150 mm cubes can be very heavy and are of significant cost. Hence additional technical staff will be required to undertake the increased level of quality control necessary both at the mixing plant and on-site. A fresh density test can be evaluated using a fine aggregate density pot. The normal 0. 01 m^3 pots will be very heavy – up to 90 kg for lead shot concrete. Test methods are the same as for standard density products though additional tamping may be required to fully compact mixes containing poorly shaped aggregates. (E. Miller, 2003)

The properties of freshly mixed HDC needs to be tested and should include the following: density, temperature, slump and air content. Specification limit for should be specified for all the important properties. (J. Goodman, 2009)

When HDC is required it is advisable that the design engineer issues an addendum specification to the standard concrete section as some aspects of its use are fundamentally different from standard concrete production.

Points for consideration:

Aggregates

Source limitation and delivery;

Cost;

Appropriate physical, chemical and petrological properties.

Concrete

Strength;

Low free w/c;

Mandatory use of super plasticisers;

Full scale laboratory trial mixes to confirm fresh and hardened properties including fresh density.

Designers should consider the implication of non-compliant mixes, particularly with regard to marginal densities. This may be importuned and some statistical safety margins may need to be included on a basis similar to those used for compression strengths. A final point to consider is the potential expense of remedial work as some grades of HDC, particularly those with iron aggregate, will be extremely difficult to remove. (E. Miller, 2003)

Table 3: Summary of typical properties of high-density concretes.

Concrete type/ Property

Unit

Barytes

Magnetite

Chilcon coarse natural sand

Chilcon coarse & fines

Fergran coarse feriron fines

Iron shot

Lead shot Non structural

Typical standard concrete comparison

Typical cement content

kg/m³

330+

200-400

360

350

300

400

500

330

Typical free w/c (+s/plasticiser)

0. 5

0. 7-0. 45

0. 45

0. 45

0. 45

0. 43

0. 34

0. 5

Typical density

kg/m^3

3500

4000

4400

5200

5300

5900

8600

2300-2400

28-day strength (100 mm cube)

Mpa

20-30

20-40

70. 0+

80. 0+

45-55

30-40

20

30-40

Indirect tensile strength 200 x 100 mm cyl.)

Mpa

2. 7

4. 0

5. 0

5. 2

6. 0 (est)

4. 5

N/A

3. 5

Young modulus

Gpa

20

20-35

40

50

50-60(est)

70(est)

N/A

20-30

Flexural strength

Mpa

3. 7

6. 0

6. 0+

8. 5

N/A

6. 5

N/A

5. 5

Dry shrinkage

%

0. 04

0. 04

Similar

Similar

0. 03(est)

0. 02

N/A

0. 04

Thermal conductivity

W/mk

1. 1

Similar

2. 5(est.)

2. 5(est.)

25-30(est)

33

N/A

1. 9

Coefficient of linear expansion

22 (Height)

10

N/A

N/A

12(est)

12. 5

N/A

8-15

5. High density concrete application and problems encountered.

5. 1 Applications of high density concretes.

Although HDC can be used for various applications (ballast blocks in domestic washing machines, radiation shielding, bridge counterweights, hospital x-ray shielding, coating of pipes, under water pipeline covering, submerged structures such as under water tunnels and for bank vault protecting), the discussion will focus on the main use of HDC in construction of a linear accelerator.

HDC was used for the 60 m^3 linear accelerator facility located in the basement of a hospital as a shield against radiation generated by the linear accelerator, which uses high intensity X-rays to kill cancer cells in patients without damaging healthy tissue. Radiation can be harmful to hospital personnel and the public if not contained in a shielded environment.

HDC was used in the walls, ceiling and foundation. A total of 85 m^3 HDC with a density of 4800 kg/m^3 was used. The steel reinforcement consisted of 11 tons placed in both directions at 300 mm centres. To achieve the required concrete density to absorb the radiation a combination of high-density aggregates steel shot (fine aggregate) and hematite iron-ore (coarse aggregate) was used. The use of high density aggregates increased the cost for 40 Mpa concrete from approximately R370. 00 to R7 600. 00 per cubic metre of concrete in 1996. (A. Balogh, 1996)

5. 2 Problems encountered.

5. 2. 1 Limited space.

The existing basement had a floor to floor height of approximately 4. 8 m. The required height totalled 5. 4 m (3. 9 m for the accelerator and 1. 5 m for the normal weight concrete slab). Due to the height of the existing basement the concrete thickness was changed from approximately 1. 525 m to 600 mm by utilising HDC. Cost analyses determined that HDC was more economical than a combination of normal weight concrete and lead shielding.

The existing hospital exterior basement wall was not designed to support the additional weight of HDC. The design was changes so that the walls and ceiling of the accelerator room be free standing. Large beam sections were incorporated in the ceiling within the required thickness by concentrating reinforcing steel in beam strips. The beams acted as cantilevers from the accelerator room to the exterior basement wall. (A. Balogh, 1996)

5. 2. 2 Mix design.

The location of the accelerator required an expertly combined high-density aggregate mix to insure that the required density for the HDC mix is obtained, be pump-able and be placed without segregation. Access to the accelerator room was limited to a 600 mm opening bored in the side walk. All the required laboratory tests related to the HDC mix design was tested to establish the suitability of the mix related to the density, strength and workability, where after the mix design was fine tuned and a trail mix pumped and placed in the foundation of the accelerator room. (A. Balogh, 1996)

5. 2. 3 Materials delivery.

The concrete trucks delivering the HDC could only be load to 30% of their capacity because of the weight of the HDC. The delivery point as well as the concrete pump was directly in front of the main entrance were the access hole was bored. Al concrete deliveries were scheduled for early Saturday mornings to minimise interference with traffic and visitors. (A. Balogh, 1996)

5. 2. 4 Concrete placement.

To ensure that the project was complete in the contract period all errors that would require the removal and replacement of the HDC was avoided at all cost. All workers were instructed not to over vibrate the HDC after being placed, to ensure segregation did not take place.

The formwork was stripped after obtaining strengths of 30 Mpa. (A. Balogh, 1996)

6. Conclusions.

HDC can be used for various types of construction projects (ballast blocks in domestic washing machines, radiation shielding, bridge counterweights, hospital x-ray shielding, coating of pipes, under water pipeline covering, submerged structures such as under water tunnels and for bank vault protecting) and although more expensive, it has its rightful place in construction.

HDC requires no additional or special equipment, plant or mixing techniques.

Quality monitoring should take place from design stage through to the production stage and special quality control measures must be in place.

Changes or addendums to standard specifications must be in place to specify the required densities and other properties.

Aggregate availability as well as the chemical composition of the intended aggregate to be used must be confirmed before designing laboratory mixes prior to the construction phase.

The cost implication in using HDC must be verified before construction as it is not a cheap general commodity.