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# Design and verification of properties of heavy-weight concrete for the production of weights

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**Abstract.** The paper deals with the design of composition and verification of the properties of heavy-weight concrete for the production of weights. Heavy weights from fine-grained heavy-weight concrete can be used as a substitute for harmful lead weights (sinkers) for fishing purposes. Lead fishing weights contaminate water, posing a risk to aquatic animals and birds. The production of fishing sinkers from heavy-weight concrete seems to be a possible substitute. A significant reduction in the use of lead fishing sinkers in the European Union is currently under preparation. The formulas of heavy-weight concrete from fine aggregate (fractions max. 2mm) were designed and tested. The consistency of concrete was designed for casting. The optimum vibration frequency of concrete compaction was determined at 75 Hz, resulting in a smooth, colourable surface. The density of the dried concrete after 28 days was  $4000 \text{ kg.m}^{-3}$  using a magnetite aggregate with an apparent density of  $5.07 \text{ Mg/m}^3$ .

## 1. Introduction

Heavy-weight concretes are concretes with a density above  $2600 \text{ kg.m}^{-3}$  [1], achieved by using heavy aggregate with a volumetric weight over  $3000 \text{ kg.m}^{-3}$  or via barite cement. Heavy-weight concretes are used as shielding concretes for radiation protection in nuclear power plants, hospitals or laboratories. Moreover, heavy-weight concrete elements are also used to load structures, such as the foundations of dynamically loaded machines, and as different weights, such as crane weights. Fishing weights (fishing sinkers) made of heavy-weight concrete are a prospective application of heavy-weight concrete as these concrete fishing sinkers can act as substitutes for widely used non-ecological lead fishing sinkers. Lead sinkers weights contaminate water, posing a risk to aquatic animals and birds. Recently, significant restrictions on the use of lead weights for fishing are being prepared by the European Union. Fishing sinkers made of heavy-weight concrete may be a possible substitute.

## 2. Ecotoxicity of Lead Weights

Because of its low melting temperature ( $327 \text{ }^\circ\text{C}$ ) and high density ( $11\,340 \text{ kg.m}^{-3}$ ), lead is an ideal material for casting fishing sinkers—if we leave out its toxicity. The problem with lead lies in its negative impacts on health; it seems that even low-level exposure can affect health. Lead is very toxic, and, when ingested, it threatens many body organs and functions. Lead poisoning has a negative impact on the functions of CNS, kidneys, immune system, heart and blood vessels. When ingested directly, e.g. from lead paint, contaminated water, food, etc., lead quickly gets into the blood and spreads throughout the body. Long-term exposure to lead can cause slackness of the musculoskeletal system (e.g. fingers,



ankles, etc.), a slight increase in blood pressure, anaemia, reduced male and female fertility and even miscarriage. For young children, low-level or long-term exposure to lead affects brain functions and causes blood disorders. However, thanks to research on lead harmfulness, this metal is restricted in several countries, even for fishing. The EU has examined the impact of fishing lead sinkers on the environment and human health, finding that lost lead weights have an impact on the environment, for, if a weight is lost in water, the lead is abraded and dissolves with time. If a sinker gets lost outside the aquatic environment, it slowly corrodes, resulting in toxic substances, especially lead sulphides and oxides. It can also lay down sediments, thus being preserved for a long time. The substitution of lead weights is difficult because lead can be shaped very well; moreover, it is heavy and, given the alternatives, cheap. Alternatives include other metallic elements (tin, bismuth, antimony, steel, brass, tungsten, etc.); however, they have their disadvantages, too. For example, zinc is also toxic, copper has a negative impact on invertebrate animals, elements like tungsten and gold are very expensive, and steel is subject to corrosion. Non-metallic alternatives include resin and polypropylene, but these are disadvantaged by their low bulk density (compared to metallic elements) and their price. Other substitutes can be plastic stone or heavy-weight concrete [2].

### 3. Components of Heavy-weight Concrete

The components of heavy-weight concrete are very individual, depending on the concrete's usage. For protection against radiation, when objects are implemented in relatively great volumes, it is necessary to prevent the concrete from overheating via the generating heat of hydration. Thus, there is a need to choose the correct type of cement (cements of higher strength class generate more heat of hydration, and cements with the R designation, which stands for high initial strength, also generate more heat of hydration than cements with the N designation—normal initial strength). It is also necessary to treat hardened concrete well, especially after high-temperature concreting. Fillers of such concretes include steel slugs, synthetically produced corundum or natural aggregates: baryte, steel ore—magnetite, hematite, etc. Heavy-weight aggregates complicate the mixing of fresh concrete, for a mixer absorbs a lower volume of filling because of the heavy weight and worse homogenization). For these very same reasons, it is possible to transport lower volumes of concrete compared to standard concrete. In addition, it is necessary to check that there is no dusting of heavy aggregate grains during concreting [3].

#### 3.1. Aggregates

A heavy-weight aggregate can be natural (rocks) or industrial. There are several general aggregate requirements:

- Guaranteed grain size distribution, density, content of crystalline water
- Defined chemical composition
- An aggregate must be of such character as to not threaten the strength and compactness of concrete
- During storage and mixing an aggregate, there should not be excessive abrasion
- The surface of an aggregate shall not reduce the bond strength of mortar and concrete
- An aggregate shall not contain substances that can degrade concrete or steel

*3.1.1. Widely used aggregates.* Baryte contains more than 85% BaSO<sub>4</sub>. Its density is within 4000 and 4300 kg.m<sup>-3</sup>. The compressive strength is about 48 MPa in average. It is not very resistant to abrasion, and it is mainly used for massive constructions that need to eliminate the impact of radiation.

Magnetite, an iron ore, contains up to 65% Fe. Its density is about 4600 and 4800 kg.m<sup>-3</sup>. The compressive strength can be up to 220 MPa.

Limonite contains  $\alpha$ -FeOOH a Fe<sub>2</sub>O<sub>3</sub> and 6 to 11% crystalline water. Its density is within 3400 to 3650 kg.m<sup>-3</sup>. The compressive strength can be up to 300 MPa.

For steel and cast iron, it is possible to use steel cuttings, waste from machining or cast iron slugs. Its advantage is its especially high density (about 7850 kg.m<sup>-3</sup>).

Corundum, with a chemical formula of  $\text{Al}_2\text{O}_3$ , can be natural or synthetic. With a density of 3600 up to 4300  $\text{kg}\cdot\text{m}^{-3}$ , it is extremely hard (9 on the Mohs scale). Corundum is used for concretes subjected to abrasion, e.g. floors.

According specific requirements, combinations of aggregates can also be used [1], [3].

### 3.2. Colour pigments

When using heavy-weight concrete for the elimination of radiation or for protection against dynamic effects, high quality is not expected, compared to architectural concrete. When using heavy-weight concrete for, e.g., weight, certain appearance requirements can arise. One such requirements can be a colour different from standard concrete; in this case, it is possible to use colour pigments. The following requirements exist for inorganic pigments:

- Colour stability in contact with concrete and weathering
- Minimal impact on concrete strength, concrete setting and hardening
- Thermal stability
- Good covering ability ensured by proper granulometry and limited aggregation of particles
- Minimal content of soluble salts ( $\text{SO}_4^{2-}$ ,  $\text{Cl}^-$ ,  $\text{SiO}_3^{2-}$ )
- Limited content of oxides devaluing the colour ( $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ )
- Good dispersion of particles with the size of 0.1  $\mu\text{m}$  to 0.2  $\mu\text{m}$ .

Pigment particles tend to gather—floculate, thereby decreasing the colouration. The intensity of colouration logically depends on a pigment dose. A common maximal effective dose is about 6 to 9% of the cement weight [4].

## 4. Fine-grained Heavy-weight Concrete

For using heavy-weight concrete for other than shielding reasons, the composition requirements are quite different from standard heavy-weight concretes. The aim of this research is to suggest and test fine-grained, heavy-weight concrete for weights production. Fine-grained concrete was chosen because of its comparatively small dimensions of weights as well as the availability of narrow fractions of a heavy-weight aggregate. An example of standard density, fine-grained concrete is the production of floor screed, where fine-grained concrete recipes are used. Requirements for final product and workability differ from those of a heavy-weight aggregate.

### 4.1. General requirements for fine-grained, heavy-weight concrete:

- As low a water factor as possible, but sufficient for good casting (the higher the factor, the more significant the segregation will be)
- Using a superplasticizer with the best effect
- Higher amounts of cement in relation to the greater specific surface of fine aggregate
- Minimal content of air both in hardened and fresh concrete (the content of air in concrete is the main factor reducing its density)
- The best possible compacting
- If a high-quality surface is required, there are considerations of quality moulds, release agents, sufficient amounts of fine proportions of rigid particles, and the use of suitable water (e.g. unrecycled)

## 5. Experimental Set-up

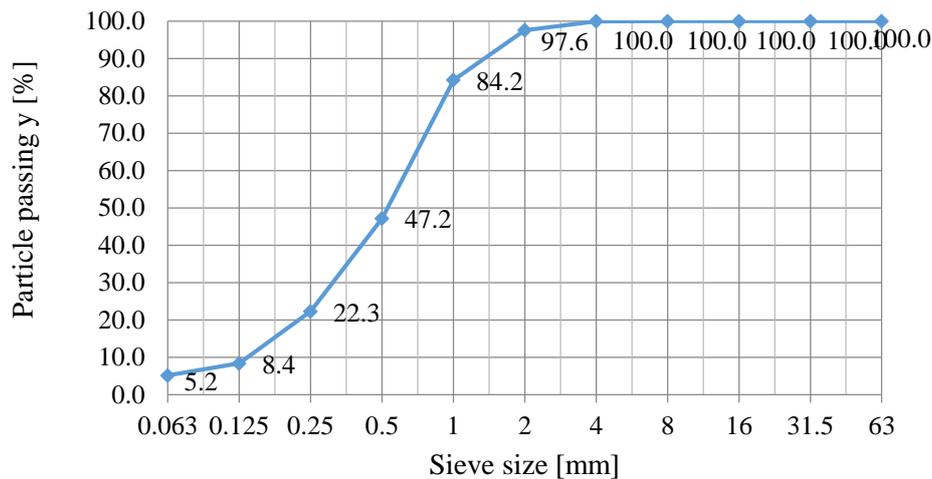
The design of a concrete recipe and the test of concrete properties consisted of these steps:

1. Selection of a heavy-weight aggregate
2. Optimisation of fine fractions and water amount to reach the maximum density
3. Setting parameters of the concrete-compacting process
4. Verification of selected superplasticizers with simultaneous effects of set accelerators
5. Selection and testing of suitable releasing agents to achieve a smooth, poreless surface

6. Experimental verification of concrete parameters—defining the density of fresh and hardened concretes and defining compressive strength after 12, 24 hours and 28 days.

### 5.1. Selection of a heavy-weight aggregate and test of its properties

For the production of heavy-weight concrete, magnetite was chosen, with Sweden as the country of origin. For the determination of particle size distribution, the sieving method was carried out according to EN 961-1 [5]. Results are stated in Fig. 1. Apparent particle density was defined according to EN 1097-6 [6]. Apparent particle density  $\rho_a$  was 5.07 Mg/m<sup>3</sup>.



**Figure 1.** Particle size distribution curve.

### 5.2. Optimisation of fine fractions and water amount to reach the maximum density

A probationary recipe of concrete was designed. The recipe was further adjusted, and it was necessary to find an optimal amount of fine proportions and water amount to secure the maximal density of concrete.

**Table 1.** The basic recipe of heavy-weight concrete.

Concrete components	Amount per 1 m <sup>3</sup> (kg)
Cement CEM I 52.5 R	530
Crush magnetite sand 0-2 mm, Sweden	3340
Water	144
Superplasticizer based on modified polycarboxylic ether (PCE)	5.3 (1 % z m <sub>c</sub> )
Liquid accelerating admixture (does not contain any added chloride ions)	21.2 (4 % z m <sub>c</sub> )
Pigment – solution (shade of red)	10.2

*Properties of superplasticizer: Homogenous liquid of orange or light-brown colour, specific gravity at 20 °C 1.06 g.cm<sup>-3</sup>, pH 4-7, CL-ion content not more than 0.1 %wt.*

*Properties of accelerating admixture: Colourless free-flowing liquid, relative density 1.26 g.cm<sup>-3</sup> at 25°C, pH ≥ 6.0 at 25°C, chloride ion content < 0.2%.*

The optimal dose of fine proportions and water was specified experimentally. The components of concretes were homogenised in a mixer with forced circulation. For compacting, the researcher used a vibrating table with a frequency converter. Because of magnetism of the used aggregate, a vibrating table with electromagnetic clamping of moulds was not used for compacting. Concrete was filled into polymer moulds.

At first, the desired amount of water was determined under constant frequency, as it was crucial to find the minimal amount of water needed at the highest possible density of concrete. The goal was to

reach the maximal compactness. Several probationary batches with different doses of water per 1 m<sup>3</sup> of concrete (140, 145, 150, 155, 160, 165 and 170 kg per 1 m<sup>3</sup>) were made, and 150 kg of water per 1 m<sup>3</sup> of concrete was defined as an optimal dose. With either a lower or higher dose of water, the weight of a mould was lower; therefore, the weight of fresh concrete was also lower. In this phase, 40 kg.m<sup>-3</sup> of stone dust was added to the mixture to achieve a high-quality surface for the concrete weight. Experimentally, it was specified that an amount higher than 40 kg.m<sup>-3</sup> increases the amount of water needed for proper workability. However, the higher amount of water was inadmissible because it can lead to a worsening of the concrete surface thanks to increased porosity, thus decreasing density. To ensure as fast a demoulding as possible, a hardening accelerator was used.

**Table 2.** The optimised recipe of heavy-weight concrete

Concrete components	Amount per 1 m <sup>3</sup> (kg)
Cement CEM I 52.5 R	530
Crush magnetite sand 0-2 mm, Sweden	3340
Filer amphibolite	40
Water	150
Superplasticizer based on modified polycarboxylic ether (PCE)	5.3 (1 % z m <sub>c</sub> )
Liquid accelerating admixture (does not contain any added chloride ions)	21.2 (4 % z m <sub>c</sub> )
Pigment – solution (shade of red)	10.2

### 5.3. Setting parameters of the concrete-compacting process

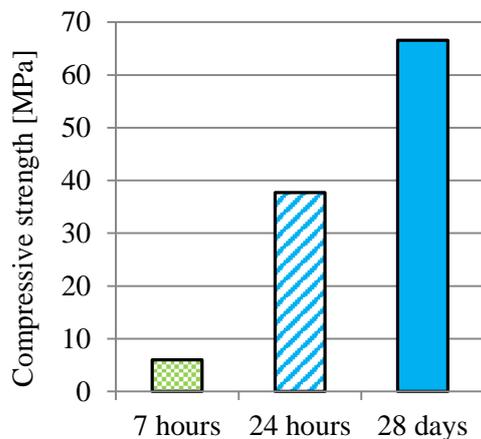
The compacting of concrete was done on a vibrating table. After defining the amount of water and fine proportions, it was necessary to define the optimal vibrating frequency, during which the best compacting can be reached. After previous experiences with the compaction of fine-grained, heavy-weight concrete, it was obvious that the ideal frequency would be between 67 Hz to 78 Hz (determined according to engine speed, monitored via an indicator on the vibrating table). During each experiment, a vibrating table was running at a constant frequency. The engine speed of a vibrating table was changed within each experiment (4000, 4300, 4500 and 4700 rpm). The definition of an ideal frequency was made according the maximal density of fresh concrete, calculated from the ratio of density of fresh concrete and the volume of a mould. A vibrating frequency of 75 Hz (4500 rpm) was selected as an optimal frequency [7].



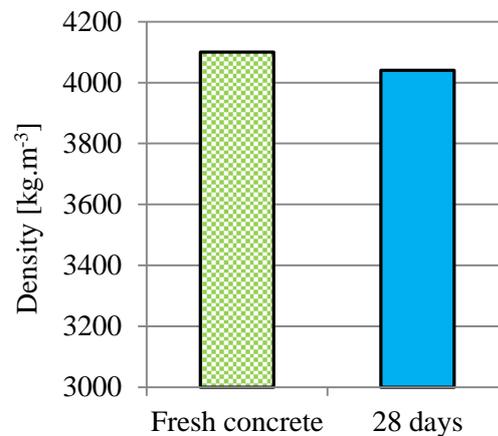
**Figure 2.** Heavyweight concrete fishing weights.

### 5.4. Experimental verification of concrete parameters

The properties of fresh and hardened heavy-weight concrete were specified. Results for compressive strength and density of concrete are shown in Fig. 3 and Fig. 4.



**Figure 3.** Compressive strength of heavy-weight concrete after 7 hours, 24 hours and 28 days.



**Figure 4.** Density of fresh and hardened heavy-weight concrete.

## 6. Conclusion

The goal of this experiment was the design and verification of heavy-weight concrete properties for the production of weights. Weights made of fine-grained, heavy-weight concrete can be used as a substitute for harmful lead fishing sinkers. The recipe design of heavy-weight concrete was made to reach the maximal compactness and density of concrete. Recipes of heavy-weight concretes from fine aggregates up to 2 mm were designed. Concretes were designed with consistency for casting with requirements of a perfect smooth surface and the possibility of coloration. The water dose for reaching the maximal compactness was experimentally specified. When using an accelerator, the compressive strength after seven hours was 6 MPa, allowing for the quick demoulding of products. The optimal compacting frequency was specified as 75 Hz. Thanks to the reduction of air content in concrete, its density increased. After 28 days, the density of the dried concrete was 4000 kg.m<sup>-3</sup> with use of the magnetite aggregate with an apparent particle density of 5.07 Mg/m<sup>3</sup>.

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