LIGHTWEIGHT AGGREGATE CONCRETE FOR PREFABRICATED ELEMENTS

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ABSTRACT

The purpose of this project was to develop new lightweight aggregate concrete types for use in prefabricated elements. In the project, crushed lightweight aggregate was used as fine aggregate instead of natural sand. The use of crushed lightweight aggregate improved of strength-density ratio and workability properties of concrete compared with conventional lightweight aggregate concrete. Semi-lightweight concrete can also be effectively produced by use of crushed lightweight aggregate. The most potential applications for the studied lightweight concrete types are hollow-core slabs and large wall elements.

Key words: crushed lightweight aggregate, lightweight aggregate concrete, strength-density ratio, prefabrication

1 BACKGROUND

Even though there have been potential applications, the use of lightweight aggregate concrete for prefabricated purposes has been limited. In the 1960s and 70s lightweight aggregate concrete was used in the prefabrication to some extent, but soon the use practically ended because of poor concrete properties. The reason for those poor properties was the unsuitability of lightweight aggregate for concrete production. The aggregate was very light (particle density less than 1000 kg/m^3) and it did not contain enough fine particles. The lightweight concrete was produced by combining natural sand and coarse lightweight aggregate. The large difference in density between the fine and coarse aggregate fractions caused several problems, such as low strength-density ratio and poor workability of fresh concrete.

Later, high-strength lightweight aggregate (density about 1400 kg/m^3) has been successfully used in the production of high-strength lightweight concrete. The density difference between the aggregate fractions is smaller than in the previous concrete type, and the cement paste properties also differ from these of the previous concrete type. However, the most common strength classes of concrete used in prefabricated elements are between 30 and 40 MPa, and for such a concrete high-strength lightweight aggregate is usually too heavy.

In 1990, Lohja Corporation, Finland and A/S Norsk Leca, Norway started a research project in which new lightweight concretes were developed for use in prefabricated structures. The Nordic Fund for Technology and Industrial Development took part in the financing of the project. The aims were to develop new lightweight concrete types and to adapt them to the prefabrication. The main interest was focused on the compressive strength classes normally used for prefabricated concrete elements (30...40 MPa), but also high-strength lightweight concretes were studied to some extent.

2 CRUSHED LIGHTWEIGHT AGGREGATE IN CONCRETE

The approach of this project to the problems of lightweight aggregate concrete was the use of crushed lightweight aggregate. The desirable grading curve of the combined aggregate can be achieved by crushing lightweight aggregate and natural fine aggregate is not needed. Consequently, no significant difference in density between fine and coarse aggregate exists, resulting in remarkable improvements in strength-density ratio and workability of concrete. Crushed aggregate also segregates less than rounded aggregate having the same particle density. Crushing reduses the natural density variation of different lightweight aggregate particles and thus homogenizes the aggregate. Crushing also affects the water absorption by lightweight aggregate. Crushing reduces the fine porous surface shell of lightweight aggregate which has the highest water absorption /1/. On the other hand, crushed lightweight aggregate increases the need of the cement paste.

The benefits of crushed lightweight aggregate are generally the smaller the higher the density of lightweight aggregate is. Therefore, in the case of high-strength lightweight aggregate the crushing does not necessarily improve concrete properties.

3 MATERIALS

3.1 Lightweight aggregate

Several different types of rounded and crushed lightweight aggregate were tested. All the lightweight aggregate types were produced by Leca expanded clay factories in Finland or Norway. Characteristics of the aggregate types are shown in Table 1. Particle densities of lightweight aggregate were determined using the water-pycnometer method /2/. In this method, the water absorption is prevented by covering aggregate particles with mineral oil.

When rounded lightweight aggregate types (E and F) were used, normal weight aggregate (N) or crushed lightweight aggregate was used as fine aggregate.

3.2 Cementitious materials and admixtures

Finnish portland cement of type P40/3 was used in most tests. The cement is a very rapid-hardening portland cement with the specific surface area around 550 m^2/kg and a compressive strength of 33 MPa and 62 MPa at the age of one day and 28 days, respectively. A condensed silica fume and a superplasticizer of type naphthalene condensate were used in the case of high-strength lightweight aggregate concrete. Polyglugol ether sulphonate was used as air-entraining admixture in some cases.

Table 1. Characteristics of the lightweight aggregate types.

Type	Description	Rounded/ crushed	Grading limits [mm]	Particle density [kg/m³]	Bulk density [kg/m³]
A	Very light ordinary lightweight aggregate	Crushed	0-2 2-4 4-8	1010 520 480	560 225 185
B	Ordinary lightweight aggregate	Crushed	0-2 2-4 4-8	1420 1080 860	705 455 415
C	Heavy ordinary lightweight aggregate	Crushed	0-2 2-4 4-8	1910 1460 1030	935 690 480
D	High-strength lightweight aggregate	Crushed	0-2 2-4 4-8	1810 [1] 1580 [1] 1530 [1]	850 [1] 645 [1] 715 [1]
E	Ordinary lightweight aggregate	Rounded	1-4 4-10	1210 800	700 435
F	High-strength lightweight aggregate	Rounded	0-4 4-8 8-12	1360 1310 1520	755 700 800

[1] = average of three different lots

4 MIX DESIGN

Altogether 129 test batches were manufactured. The mix design varied according to the density and compressive strength of the test concrete. Some typical mix designs for different density and compressive strength combinations are presented in Table 2.

Table 2. Typical mix designs for different density and compressive combinations.

Comp. strength [MPa]	Air-dry density [kg/m³]	Cement [kg/m³]	Lightweight aggregate Type [vol-%]			Normal weight aggregate [vol-%]	Effective water [kg/m³]	Admixture Type Dosage [%]
			0-2	2-4	4-8			
20	1200	450	A 45	A 15	A 40	0	230	-
30	1400	450	B 50	B 15	B 35	0	220	-
30	1800	400	B 50	-	-	50	205	-
40	2000	400	B 30	-	-	70	200	-
40	1500	450	B 45	F 15	F 40	0	215	-
60	1800	400	-	F 15	F 45	40	175	SP 1.5

5 COMPRESSIVE STRENGTH AND DENSITY

As mentioned earlier, the main interest of the project was focused on the compressive strength classes ranging 30...40 MPa, hut several tests outside this range were prepared. Fig. 1 shows the compressive strengths and air-dry densities of all the test concretes.

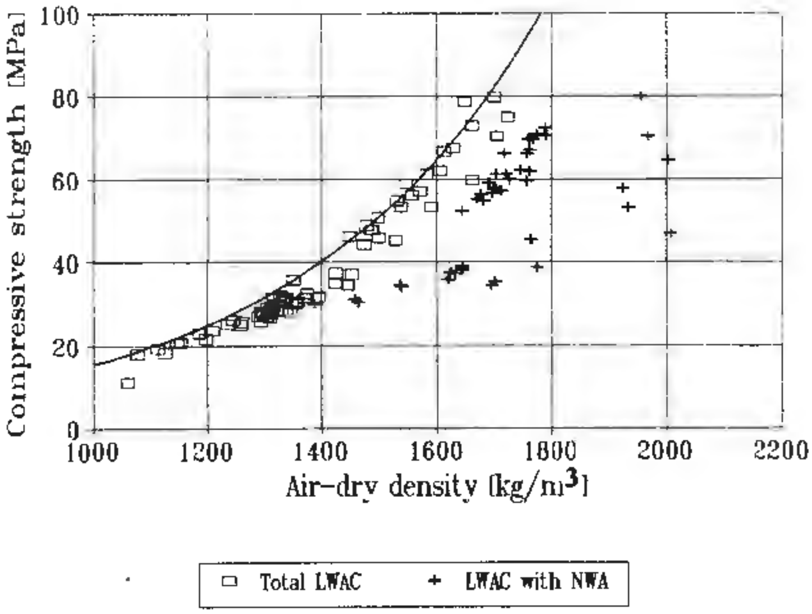

Fig. 1. Compressive strengths and air-dry densities of all the test concretes. An estimated theoretical maximum compressive strength curve from /1/ is also presented.

The strength-density ratios of the test concretes were estimated by comparing each comhination of compressive strength and air-dry density with the estimated theoretical maximum compressive strength curve. The curve was prepared based on the results of the project, those of previous tests and results available from literature.

According to obtained results, the compressive strength of lightweight aggregate concrete is primarily controlled by the particle density of lightweight aggregate. The proportion of normal weight aggregate affects the compressive strength, but not strongly. Especially when a light lightweight aggregate type is used, the effect of normal weight aggregate is low. The effect of the cement paste strength (water-cement ratio) is significant only if high-strength lightweight aggregate is used.

The use of normal weight aggregate has only a slight effect on compressive strength but a strong effect on density. Consequently, a high strength-density ratio can be achieved only if merely lightweight aggregate is used as aggregate. According to the tests, the normal weight aggregate content needed to correct the defective grading curve of rounded lightweight aggregate increases the density of concrete about 200 kg/m³. This corresbonds a decrease of strength-density ratio by about 20 MPa. Principally, both crushed and rounded lightweight aggregate give the same strength-density ratio, but because fine rounded lightweight aggregate is not available, the best ratios are achieved by using crushed fine aggregate.

It is not always necessary to achieve the highest posssible strength-density ratio. We often have a minimum demand for the compressive strength and a maximum limit for the density of concrete. For example, a concrete having a density of about 2000...2200 kg/m³ is sometimes needed in the production of large slab elements in order to be able to lift them. This kind of concrete is called semi-lightweight concrete, lightened concrete or modified normal density concrete, and it is normally produced by using only a small proportion of coarse lightweight aggregate. However, an extensive segregation of lightweight aggregate is a common problem for such a concrete. Another approach is to use crushed lightweight aggregate as fine aggregate. The density of concrete can be varied within a wide range (e.g. from 1900 to 2400 kg/m³) by varing the proportion of lightweight aggregate.

6 DURABILITY TESTS

A theoretic examination of durability properties of lightweight aggregate concrete is more difficult than that of normal weight concrete. Both the lightweight aggregate and the cement matrix affect the durability properties of lightweight aggregate concrete, and the effects are often opposite. In addition, the test method may affect the obtained test results, e.g. in the case of freeze-thaw resistance. In the project, the freeze-thaw resistance, carbonation and shrinkage induced cracking were considered as the potential durability problems of lightweight aggregate concrete usable in the prefabricated structures.

6.1 Freeze-thaw resistance

Lightweight aggregate concrete consists of two porous component: hardened cement paste and lightweight aggregate. The quality of the cement paste in lightweight concrete is generally better than that of cement paste in normal weight concrete, because the lower strength of lightweight aggregate has to be compensated by stronger cement matrix. In addition, the water absorption by lightweight aggregate improves the quality of the transition zone. Although lightweight aggregate is porous, it hardly works as protective porosity, because the spacing factor is too high. Lightweight aggregate in concrete contains water to some extent. The water content depends on the water absorption and especially on the initial moisture content of lightweight aggregate. The water inside the aggregate may have a harmful effect on the freeze-thaw resistance and especially on the fire resistance of concrete. To sum up, the cement matrix of lightweight aggregate concrete has generally a positive effect on the freeze-thaw resistance and the lightweight aggregate may in turn have a negative effect. The combined effect may be positive or negative.

The freeze-thaw resistance of the test concretes were determined by comparing flexural tensile strengths of freeze-thawed and water-cured test beams ($100 \cdot 100 \cdot 500$ mm³) /3/. The freeze-thaw tests were started at an age of 28 days and continued 100 cycles. If the tensile strength ratio was 2/3 or more, concrete was considered to be freeze-thaw resistant.

According to the obtained results the freeze-thaw resistance of lightweight aggregate concrete decreases with the decreasing particle density and increasing proportion of lightweight aggregate. Thus, the freeze-thaw resistance of non-entrained lightweight concrete may not be satisfactory, if the compressive strength of concrete is less than about 35 MPa. Fig. 2 shows the flexural strength ratio as a function of the compressive strength of concrete (particle density and proportion of lightweight aggregate have been altered, effective water-cement ratio has been kept constant).

The adequate freeze-thaw resistance can be achieved by air-entraining. When relatively light lightweight aggregate (type B) was used, an air content of 80...100 dm^3/m^3 was enough to guarantee an adequate frost resistance. The minimum air content was lower for denser aggregate types. However, air-entraining of lightweight aggregate concrete has some practical problems in achieving constant and known air content.

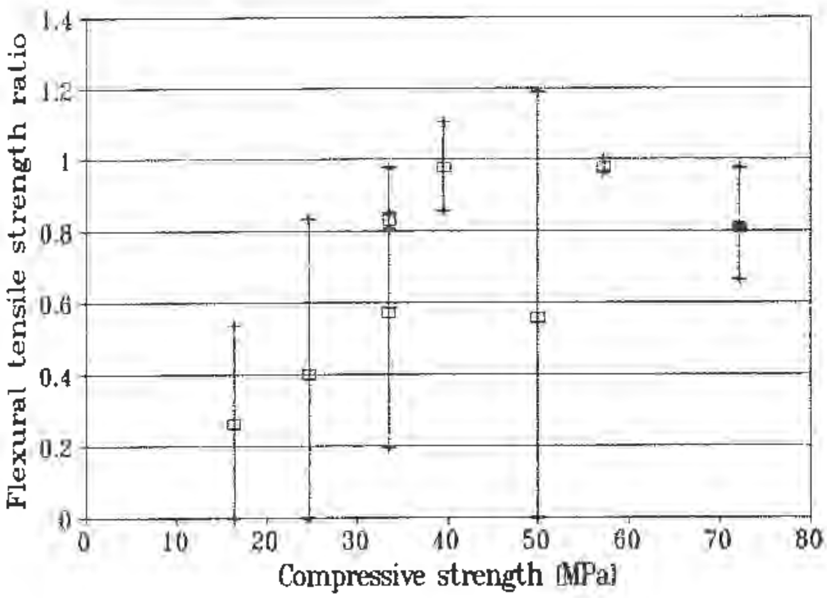

Fig. 2. The dependence of freeze-thaw resistance on the compressive strength of concrete. Particle density and proportion of lightweight aggregate have been altered, effective water-cement ratio has been kept constant. 2 + 2 beams were tested /1/.

6.2 Shrinkage induced cracking

Lightweight aggregate concretes have been reported to be sensitive for the shrinkage induced cracking /4, 5/. The cracking is obviously caused by differential shrinkage. The final shrinkage of lightweight aggregate concrete is greater than that of normal weight concrete but the shrinkage process is slower. Thus, in case of lightweight aggregate concrete, a greater shrinkage gradient between concrete surface and concrete core will be developed. Further, the tensile strength of lightweight aggregate concrete is generally smaller than that of normal weight concrete /6,7/.

The risk of shrinkage induced cracking was increased with decreasing particle density and increasing proportion of lightweight aggregate. However, the main factor controlling the shrinkage induced cracking was the type and content of cementitious material. The cracking was increased with increasing cement content. Therefore, high cement contents should be avoided in the production of lightweight aggregate concrete. The use of mineral admixture, e.g. fly ash, decreased the risk of cracking.

6.3 Carbonation

The carbonation may cause problems only when relatively light lightweight aggregate is used. High-strength lightweight aggregate concretes have generally a very low rate of carbonation.

In the project, the carbonation of test concretes was primarily controlled by the properties of cement paste. Lightweight aggregate has obviously a higher air permeability than normal weight aggregate, but the lower water-cement ratio needed in lightweight aggregate concrete practically compensates the difference. The depths of carbonation were determined on thin-sections. Randomly 10 + 10 values from the surface and side of each specimen were measured. The test specimens were water-stored for two days after demoulding and then air-stored (45 % RH) until testing, which took place at an age of 6 months. Fig. 3 shows the depth of carbonation as a function of compressive strength.

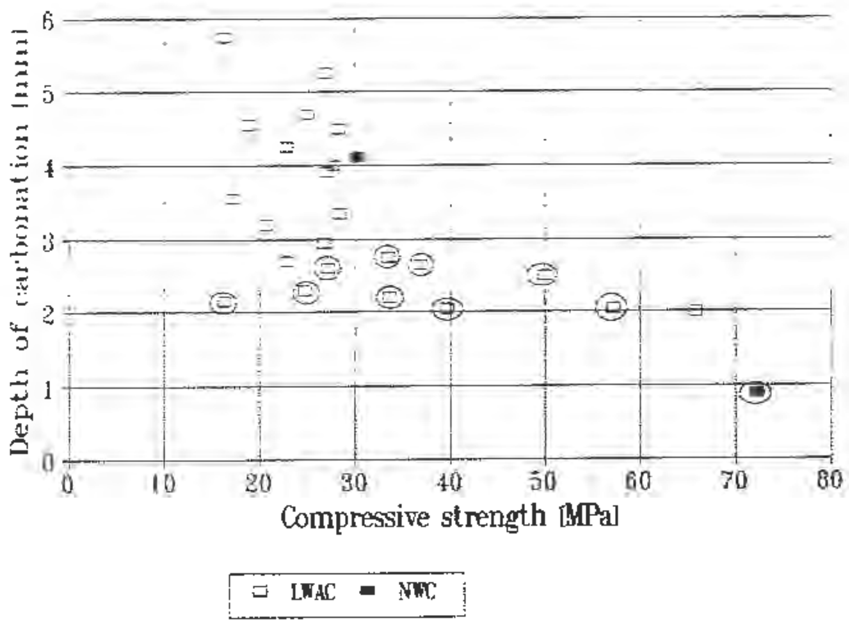

Fig. 3. The dependence of the depth of carbonation on the compressive strength of lightweight aggregate concrete. Two normal weight concretes are also included. The batches marked with ○ have equal cement contents (= 450 kg/m³) /1/.

7 WORKABILITY

The workability of lightweight aggregate concrete greatly differs from that of normal weight concrete. Four main differences can be specified:

- concrete in uncompacted stage
- the compaction of concrete
- the segregation properties of concrete
- workability loss caused by water absorption by lightweight aggregate

7.1 Workability loss

In the present project the main difference between workabilities of lightweight aggregate concrete and normal weight concrete was the workability loss caused by the water absorption by lightweight aggregate. The water absorption is not only dependent on the properties of lightweight aggregate, but also on the quality and quantity of cement paste, and on the mixing procedure of concrete /8/. The highest workability loss was measured with the aggregate type having a fine porous surface shell and a relatively small porous inner structure (rounded high-strength lightweight aggregate, type F). Rounded ordinary lightweight aggregate (type E) also had a higher workability loss than the corresbonding crushed lightweight aggregate (type B). Crushed lightweight aggregate has less surface shell, which is the essential part for water absorption. When crushed lightweight aggregate (type B) was used, water absorption mainly occurred during mixing, and the workability loss was relatively small. But when rounded high-strength lightweight aggregate (type F) was used, the workability loss was fast.

7.2 Segregation

The possible great density difference between mortar matrix and coarse lightweight aggregate causes a risk of segregation. The risk is especially high when light lightweight aggregate is used. With crushed fine lightweight aggregate, the density difference and thus also the risk of segregation can be essentially reduced. No significant segregation was noticed when crushed lightweight aggregate was used as fine aggregate.

7.3 Compaction

The compaction of lightweight aggregate concrete is generally slower and more difficult than that of normal weight concrete. The difference is not so great with rounded high-strength lightweight aggregate (type F). When light (type A) or harshy angular (type D) crushed lightweight aggregate was used, the compaction was very difficult. The finishing of the lightweight aggregate concrete surface also took more time and the final result even so was not as good as in that of normal weight concrete.

8 MATERIAL COSTS

An important disadvantage of lightweight aggregate concrete is its clearly higher material costs compared with normal weight concrete. The higher material costs are caused by higher cement content and more expensive aggregate in lightweight aggregate concrete. For example, when comparing material costs of lightweight aggregate concrete and normal weight concrete having the same compressive strength, the following results can be calculated (f_c = 30 MPa, ρ_{LWAC} = 1300 kg/m^3):

- total material costs of lightweight concrete are 2.25 times higher
- cost of cementitious material of lightweight concrete is 1.55 times higher
- cost of aggregate of lightweight concrete is 3.2 times higher
- 75 % of increase of material costs of lightweight concrete are caused by more expensive aggregate

The material costs are strongly dependent on the proportion of lightweight aggregate and when merely lightweight aggregate is used, the material costs are 2...2.5 times as high as than the material costs of normal weight concrete with the same compressive strength.

9 ADAPTING THE CONCRETES FOR PRODUCTION

The aims of the project were to develop new lightweight aggregate concretes and adapt them to the prefabrication. The higher material costs of lightweight aggregate concrete have to be compensated by the benefits of lighter weight. The lightness of concrete can be advantaged in smaller dimensions of concrete elements and/or the other structures. The transportation and assembling costs also decrease with decreasing density of concrete. And there are some applications where lightweight concrete is practically the only possibility to produce the desired structure.

The material technological part gave two new lightweight concrete types. In addition, high-strength lightweight concrete can be used in some applications. Consequently, the following three lightweight aggregate concrete types were seen potential in the prefabrication purposes:

A Lightweight aggregate concrete
- crushed fine lightweight aggregate
- compressive strength: 30...40 MPa
- density: 1400...2000 kg/m^3

B Semi-lightweight aggregate concrete
- crushed lightweight aggregate
- compressive strength: 40...60 MPa
- density: 2000...2200 kg/m^3

C High-strength lightweight aggregate concrete
- rounded high-strength lightweight aggregate
- compressive strength: 50...80 MPa
- density: 1600...2000 kg/m^3

Technical and economical examinations were made and the following element types were selected for further examinations /9/:

1. Light, suspendable facade panels (concrete type A)
2. Large, heavy wall elements (concrete type A)
3. Hollow-core slabs (concrete type B)
4. Large TT-elements (concrete type B)

Hollow-core slabs and large wall elements were considered to be the most promising element types for lightweight aggregate concrete. All the mechanical requirements were met in the full-scale tests.

10 SUMMARY

The objective of the project was to develop lightweight aggregate concretes for prefabrication. The interest were focused on the compressive strength classes from 30 to 40 MPa, which are the most commonly used for prefabricated elements.

Expanded clay lightweight aggregate the way it is produced does not contain enough fine particles to be used in concrete. Conventionally, the unacceptable grading curve has been corrected by using fine normal weight aggregate. However, two different aggregate types cause segregation problems and lower attainable strength-density ratio. In this project, the defective grading curve was corrected by aid of crushed lightweight aggregate.

The particle density of lightweight aggregate is the most important factor controlling compressive strength of lightweight aggregate concrete. The use of normal weight aggregate greatly lowers the strength-density of concrete. According to the test results, the normal weight aggregate content needed to correct the grading curve of rounded lightweight aggregate lowers the compressive strength by about 20 MPa compared with lightweight aggregate concrete containing merely lightweight aggregate and having the same density.

Freeze-thaw resistance, shrinkage induced cracking and carbonation of concrete were considered to be potential durability problems when using lightweight aggregate concrete for prefabricated elements. Air-entraining is needed to guarantee adequate frost resistance for the lightweight aggregate concrete. Shrinkage induced cracking can be limited to an acceptable level by reducing the cement content of concrete. The rate of carbonation was more strongly controlled by the cement paste properties than the aggregate properties.

The main workability problems were segregation and workability loss caused by the water absorption by lightweight aggregate. The risk of segregation can be essentilly reduced by avoiding using normal weight aggregate. The material costs of lightweight aggregate concrete are 2...2.5 times as high as the material costs of normal weight concrete having the same compressive strength. The additional cost is mainly caused by more expensive aggregate.

In the material technological part of the project, two new lightweight aggregate types were developed: lightweight aggregate concrete (30...40 MPa, 1400...2000 kg/m^3) and semi-lightweight concrete (40...60 MPa, 2000...2200 kg/m^3). Both concrete types contain crushed fine lightweight aggregate. The developed lightweight aggregate concrete types were found suitable for prefabrication. Hollow-core slabs and large wall elements were considered to be the most potential applications for lightweight aggregate concrete. All the mechanical requirements were met in full-scale tests.

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