14 Lightweight Aggregate Concrete

Introduction

- The use of lightweight (LWAC) can be traced to as early as 3,000BC, when Mohenjo-Daro and Harappa were built during the Indus Valley civilization.
- In Europe, the use of LWCA occurred 2,000 years ago when the Romans built Pantheon, the aqua ducts, and the Colosseum in Rome.
- The pumice（軽石）is still used today in certain countries, such as Germany, Italy and Japan.
- In some places , like Malaysia, palm oil shells are used for making LWAC.

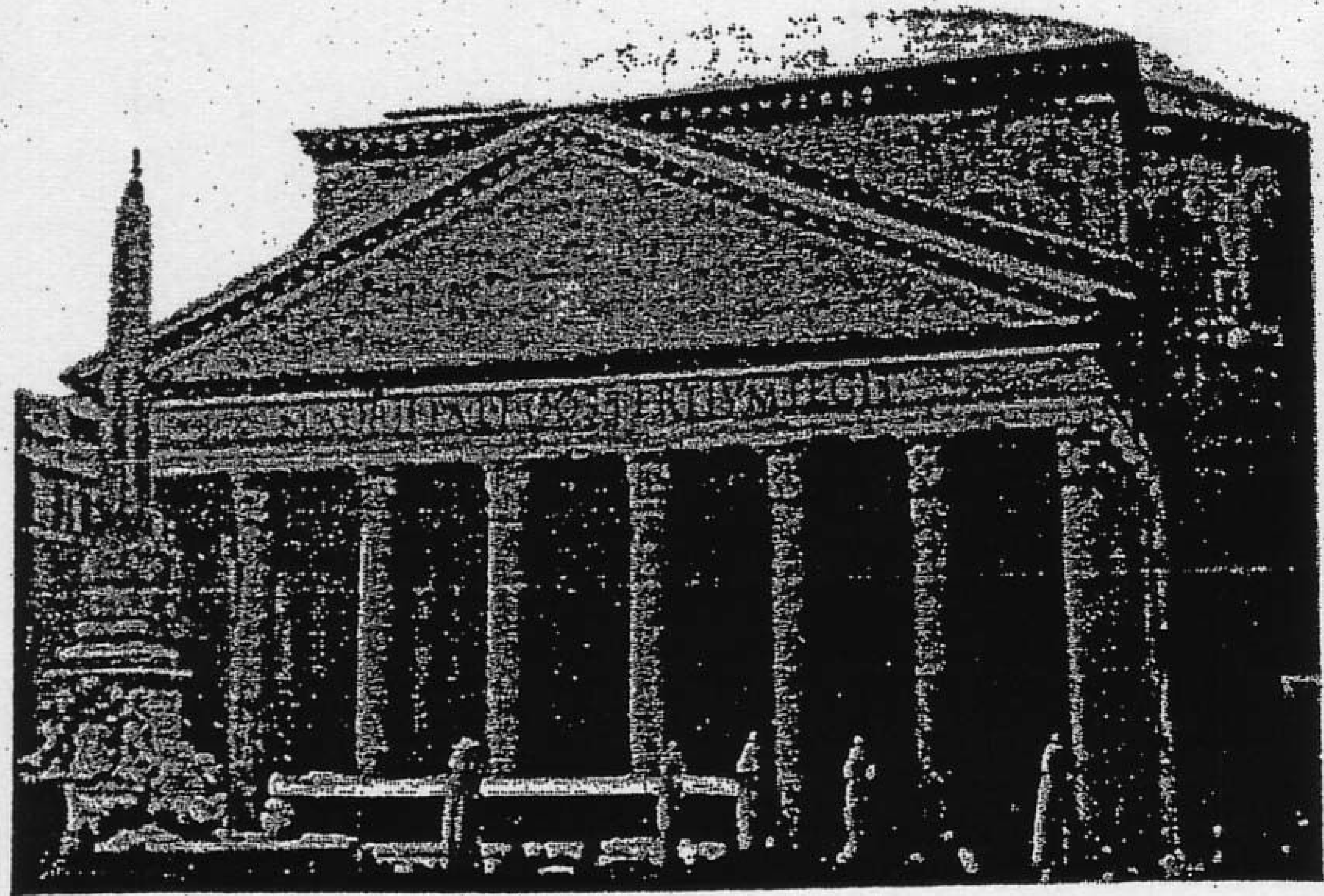


Figure 1.3. The Roman temple, Pantheon, built in A.D. 118.

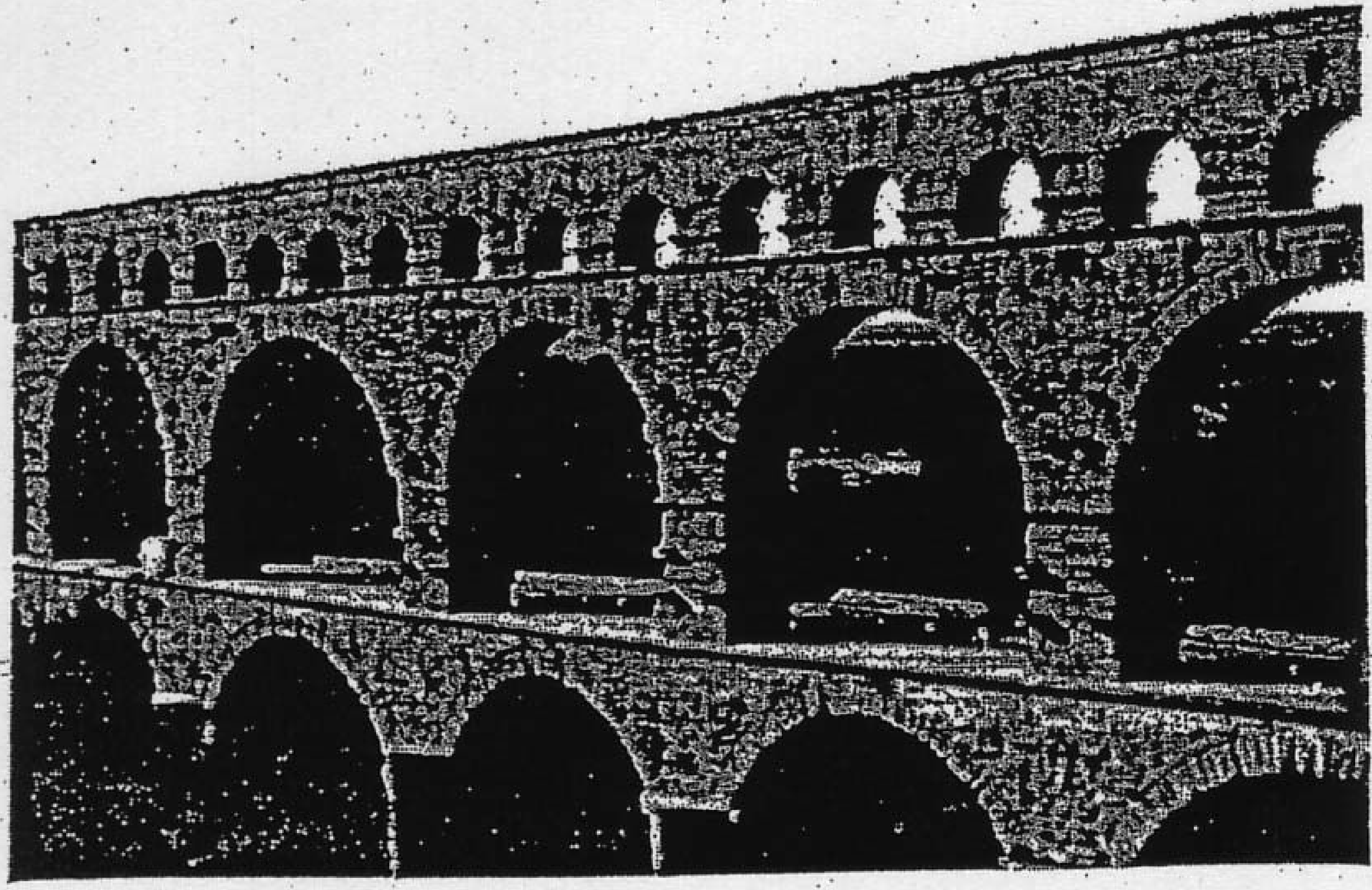


Figure 1.4. The prestigious aqueduct, Pont du Gard, built in ca. A.D. 14.

Cont.

- Earlier lightweight aggregates (LWAs) were of natural origin, mostly volcanic: pumice, tuff（凝灰岩）, etc.
- They function as active pozzolanic materials when used when used as fine aggregates.
- Techniques have been developed to produce them in factories. These are produced from the natural raw materials like expanded clay, shale, slate, etc., as well as from by-products such as fly ash, blast furnace slag, etc.
- Today, lightweight aggregates are produced in a very wide range of densities varying from 50kg/m3 from expanded perlite（真珠岩）to 1000kg/m3 for clinkers. It is possible to make LWAC of 80Mpa compressive strength

Cont.

- Nearly all LWACs are fire resistant. In addition, depending upon the densities and strength, the concrete can be easily cut, nailed, drilled, and chased with ordinary wood working tools.
- Lightweight concrete is expensive, but the cost is calculated not just on the basis of aggregates or LWAC.
- The bond between the aggregate and the matrix is stronger in the case of LWAC than in normal concrete. Cement paste penetrate inside the aggregates due to their porous nature. Thus, there is very little or no ITZ between the aggregates and the matrix

2. Production of lightweight aggregates and its properties

1.0 Introduction

- LWA can be divided into two categories:
- 1.Those occurring naturally and are ready to use only with mechanical treatment, i.e., crushing and sieving.
- 2.Those produced by thermal treatment from either naturally occurring materials or from industrial by-products, waste materials, etc. The industrial by-products are pulverized fly ash, blast furnace slag, industrial waste, sludge, etc. These are produced either by expansion or agglomeration. The heat treatment is carried out in different types of industrial furnaces, such as rotary kilns.

2.0 Industrial kilns – omitted -

3.0 Natural lightweight aggregates

- 3.1 Pumice —軽石—
- Pumice is formed when the molten SiO_2 rich lava from the explosive eruption of a volcano cools. It is called " supercooled liquid".
- The low density of pumice is due to the presence of gas bubbles.
- 3.2 Palm oil shells
- The use of agricultural waste as aggregates can provide an alternative to conventional methods for production of lightweight aggregates.
- The palm oil shells are hard and are received as crushed pieces as a result of the process used for extracting the oil.
- The 28 days strengths vary 5.0-19.5Mpa.

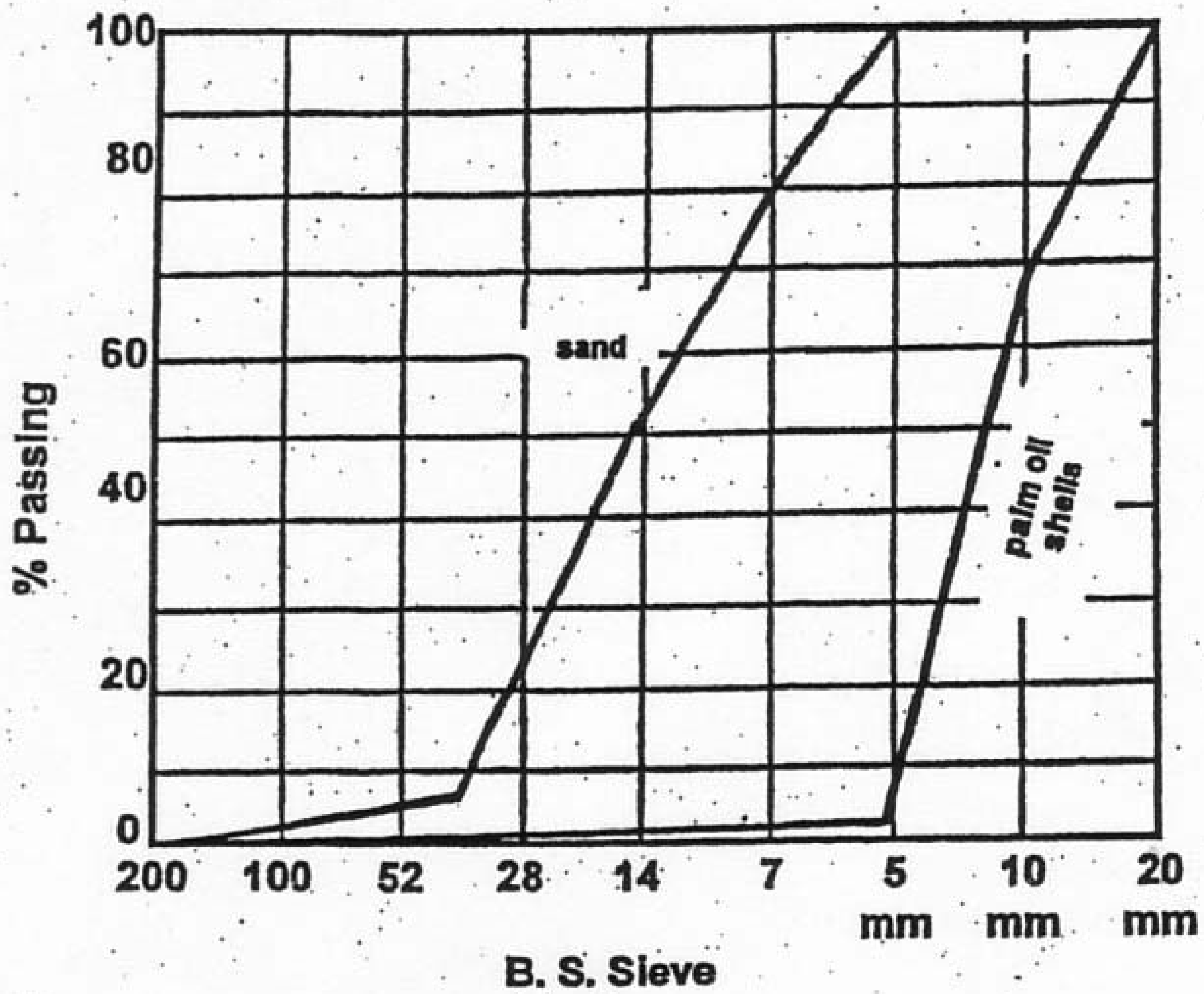


Figure 2.3. Particle size distribution curves for palm oil shells and sand.[6]

3.3 Crushed burnt bricks

- Burnt bricks are used in construction at Mohenjo-Daro, 2800 BC.
- (In Bangladesh, this material is used as aggregates in present.)

4.0 Production techniques

- 4.1 Natural materials
- ---- New LWA from perlite（真珠岩）: In Japan, new aggregates are developed which are made of perlite. They are called Asano Super Light (ASL). 残念ながら、販売不調のもよう。

4.2 LWA from industrial by-products

- - Expanded pelletized（小球化）fly ash aggregates
- Lower quality fly ash with a higher and variable carbon content is used for making LWA by adding extra pulverized coal to bring the carbon content to about 12%, and then pan pelletizing and heat treating then on a traveling grate（火格子）.
- - Lightweight aggregates from blast furnace slag (Palletized slag)
- Due to the growing demand for aggregates worldwide, research is being carried out.
- LWA from slag in Canada, Russia, are introduced.
- Also, LWA from dredging waste is introduced.

3. Supplementary cementing materials

- 1.0 Introduction
- These supplementary materials are known to contribute the strength and durability.

2.0 High performance cement

- There are different types of cements varying in their mineralogical compositions.
- The addition of mineral admixtures like silica fume produces cement with high strength.
- This is of interest for off-shore construction where high strength and high performance are required.
- A Norwegian cement company (NORCEM) has developed high strength cement.
- Apart from special cement, silica fume, 5-8% by weight percent is added to all high performance LWAC in Norway.

3.0 Mineral admixtures

- fly ash, blast furnace slag, and silica fume, sometimes rice husk ash, colloidal silica
- 3.1 Hydration of fly ash cement
- 3.2 Hydration of blast furnace slag cement
- 3.3 Hydration of silica fume
- SiO_2 rich hydrate is deposited in layers or films on the silica fume particles.
- C-S-H , having a C/S ratio of about 1 (usually 1.5-2.0), have been reported to form at 20℃ in 24 hours and after mixing with water and at 38℃ in only 6 hours.

3.4 Hydration of cement with colloidal silica; cembinders

- Cembinders are aqueous silicic acid suspensions（珪酸懸濁液）. The specific surface are of the particles is in the range of 50 to about 200m2/g（SFの１０倍). Cembinder reacts chemically with the calcium hydroxide during hydration of Portland cement and produces C-S-H.

4.0 LWAC with a mineral admixture -About sintered-焼結- fly ash aggregates

- 4.1 Details of the materials used
- The used mix proportions are shown in Table3.1.
- 4.2 Strength properties
- The addition of a highly reactive pozzolan, such as silica fume, can compensate for the loss of early strength as shown in Tables3.2 and 3.3（Table3.1 Mix proportions).
- The fly ash mix F shows the highest flexural strength at 6 months, compared to all other mixes, and this is considered to be due to the better bond between the fly ash LWA and the fly ash cement matrix.

Table 3.1. Mix Proportions of LWAC[21]

No Free	Cement kg/m³	SF kg/m³	Slag kg/m³	PFA kg/m³	Sand kg/m³	Lytag™ kg/m³	W/B
N	350	—	—	—	635	715	0.4
F	300	20	—	30	635	715	0.4
S	300	20	30	—	635	715	0.4
SF	250	10	45	45	635	715	0.4

Table 3.2. Compressive Strength at Different Ages, MPa

Mix No.	Age of Concrete, days						
	1	3	7	28**	28*	180**	180*
N	31.3	36.6	48.0	53.8	59.0	61.1	61.7
F	27.3	34.3	42.8	48.0	53.8	59.9	62.1
S	25.0	39.1	41.7	50.4	55.6	63.2	65.6
SF	17.4	31.3	36.5	46.1	49.2	59.4	56.6

** Wet curing, * Wet/air curing

Table 3.3. Flexural Strength with Time, MPa

Mix No.	Age of Concrete, days						
	1	3	7	28**	28*	180**	180*
N	4.35	5.01	5.52	5.73	2.97	5.48	5.55
F	3.78	4.96	5.33	5.75	2.60	5.77	5.80
S	4.44	5.11	5.27	5.95	2.91	4.93	5.25
SF	3.49	4.62	4.85	5.43	3.39	5.13	5.36

** Wet curing, * Wet/air curing

- 4.3 Elastic modulus
- The elastic modulus of all the concrete containing supplementary cementing materials has a higher dynamic modulus than the Portland cement concrete by about 10 to 15%.
- One of the unique features of the PFA (Pulverized fly ash) light weight aggregate concrete is the excellent aggregate-matrix bond that develops between the fly ash aggregate and Portland cement or Portland cement fly ash matrix.

- 5.0 Superplasticizers (SP)
- Superplasticizers are surface active agents and have water-reducing characteristics.
- 5.1 Influence of cement type on superplasticizing admixtures
- Superplasticizers behave differently with different cements.
- Especially, the type of sulfate in the cement has a major effect on the viscosity and yield. Claisse show that the anhydride (CaSO4) gives substantially greater values than the gypsum (CaSO4-2H2O).

- 6.0 Concluding Remarks
- With the growing demand on the strength and durability properties of LWAC, different binder system have been developed and used.

- 4 Mix proportion - omitted -

5. Production Techniques (LWA concrete)

1.0 Introduction

- The production of lightweight aggregate concrete has been expanding, and now includes all types – from no fines concrete of low density, mainly for block production, to structural concrete with densities from 1000 to 2000 kg/m3 and compressive strength up to 80MPa.
- There have been difficulties pumping LWAC because the pump pressures forces water into the porous aggregates particles resulting in an increased stiffness in the concrete which blocks the pipes.
- So knowing the absorbency of the LWA before production is critical to the process.
- A very high strength cement paste does not compensate for a lightweight aggregate of low density and strength.

LWA and its supply

2.1 Bulk density and particle density

- The tests for density and the moisture content need to be updated from time to time and always at the delivery of fresh materials.

- 2.2 Moisture content of the LWA
- The absorption of water by the LWA particles is significant in concrete production.
- It is logical to soak the aggregate before mixing or to ask for delivery of very wet aggregates.

Cont.

- However, this is not always a good solution for all concrete production.
- For house construction, a high water content in the LWA results in a long drying time of the concrete components and high humidity indoors.
- Even though, the absorption may be reduced by soaking the aggregates. There are a number of methods used.
- Pre-wetting in the mixer is the least effective methods, but it is commonly used.
- The most effective method is vacuum-soaking.

3.0 Remarks on mix design

- There are several advantages in using LWA.
- These are due to their bond with the cement paste and closeness of their coefficients of thermal expansion and the modulus of elasticity compared to those of dry cement paste.
- On top of it all, there is a reduction in permeability, shrinkage cracking, and improved durability

3.1 Lightweight fines

- Normally, the LWA is confined to the coarse fraction which means a particle size from 2mm to 4mm and sometimes even larger.
- In such cases, use of lightweight fines may be the optical solution.

3.2 Pumped concrete and its design

- Pumping of fresh concrete has been widely used and the high pressure during pumping presses water into the porous LWA.
- Mineral admixtures, for example, ground-granulated blast furnace slag or fly ash, as a fines addition influences workability and is cost effective.
-

- 4.0 Batching -omitted-
- 5.0 Transportation and placing of concrete -omitted-
- 6.0 Testing of LWAC related to production -omitted-
- 7.0 Concluding Remarks – omitted -

6. LWAC microstructure

1.0 Interfaces in Concrete

- The presence of these materials gives rise to a wide variety of interfaces in concrete. The principal ones are listed below:
- the various phases that make up hcp.
- 1.the hcp and the still-unhydrated cement grain.
- 2.the hcp and the unreacted portion of the pozzolanic materials.
- 3.the hcp and aggregates
- 4.the hcp (or mortar) and the discontinuous fibers.
- 5.the hcp (or concrete) and the steel reinforcement.
- 6.the solid phases and either air or water, which will not be considered further in this review.

1.1 The nature of the interfacial regions in concrete

- There are generally large crystals in the interfacial zone, with a preferential orientation. But this should not be taken as the inherent property of interfaces; more likely ot occurs because there is extra space at the bleeding of water.
- Many models of interfacial zones have been presented which vary from each other. A few of these models are shown in Fig.6.1.
- With an interfacial zone thickness equaling 50um, most of the hcp lies in the interfacial zone.

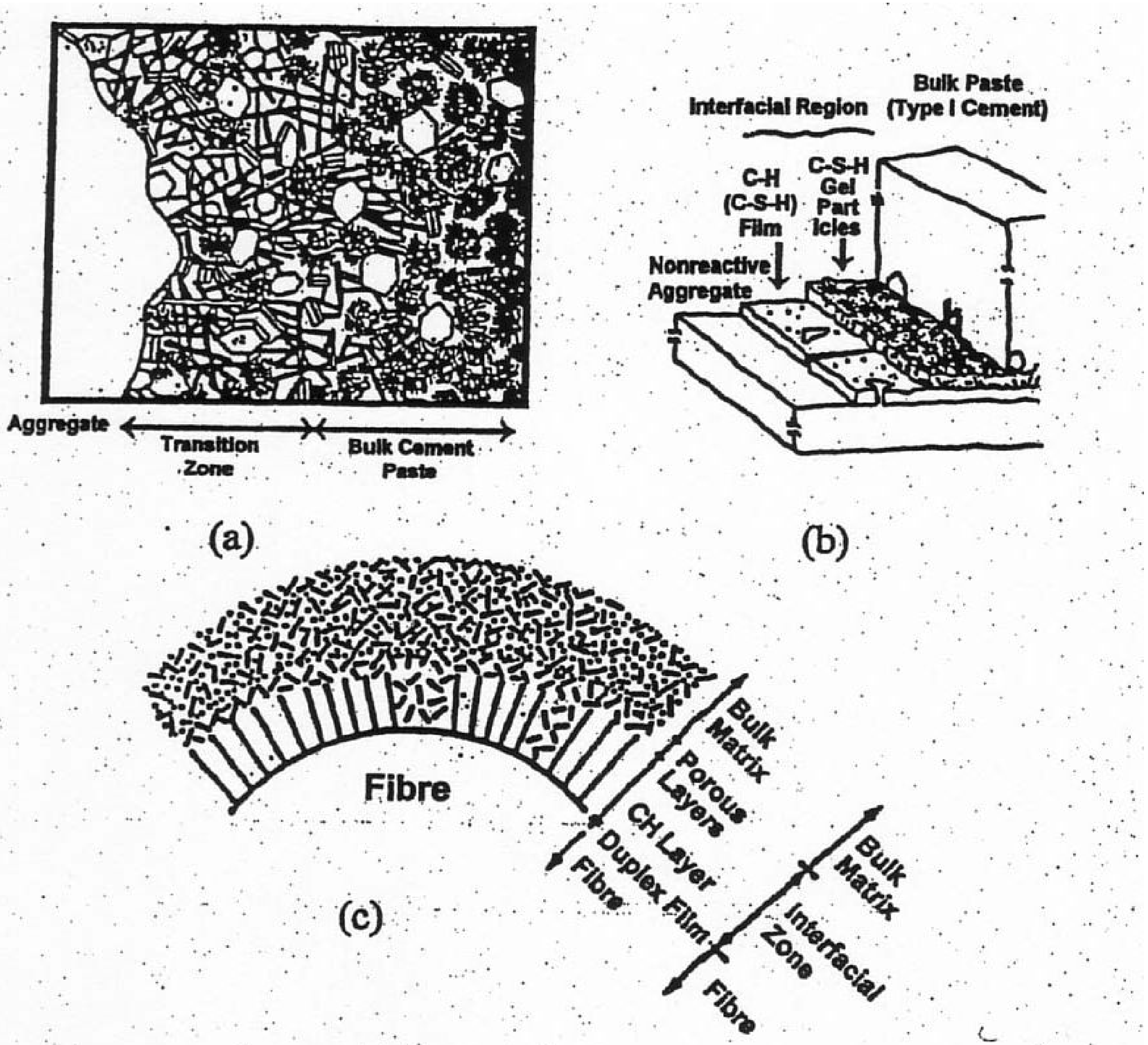


Figure 6.1. (*a*) Diagrammatic representation of the transition zone and bulk paste in concrete,[1] (*b*) interfacial region formed between a non reactive silica substrate and type I cement paste,[3] (*c*) interfacial zone at the steel fiber interface.[4]

1.2 Cement-Aggregate bond

- It is generally agreed that the interface between the hcp and the aggregate is the “weakest link” in concrete.
- The cement aggregate interfacial zone has an open morphology compared to the bulk hcp.
- The interfacial zone contains large crystals of portlandite, $Ca(OH)_2$, preferentially oriented so as to create planes of weakness.
- Bleed water often accumulates beneath the larger aggregate particles, creating additional planes of weakness.
- In normal concrete, cracks propagate preferentially in the interfacial region, generally a few micrometer away from the aggregate surfaces themselves.

Cont.

- In LWAC, on the other hand, the cracks tend to propagate in a straight line right through the aggregate particles in the crack path. In this case, the aggregates themselves are weaker than either the hcp or the interfacial region.
- Most studies have shown that increasing the bond strength increases the concrete strength, but these increases tend to be moderate, in the range of 20-40% at best from "no bond" to "perfect bond".

- One simple relationship between bond strength and either compressive or flexural strength was developed.
- It has form
- $F = b0 + b1M1 + b2M2$ Eq.(1)
- Where F: concrete strength in compression or flexure (psi)
- b0,b1,b2: linear regression coefficients, 480, 2.08, 1.02, for compression, 290,0.318,0.162, for flexure
- M1: modulus of rupture of the paste (flexural strength)
- M2: modulus of rupture of the aggregate-cement border
- A plot of this equation is shown in Fig.6.2.

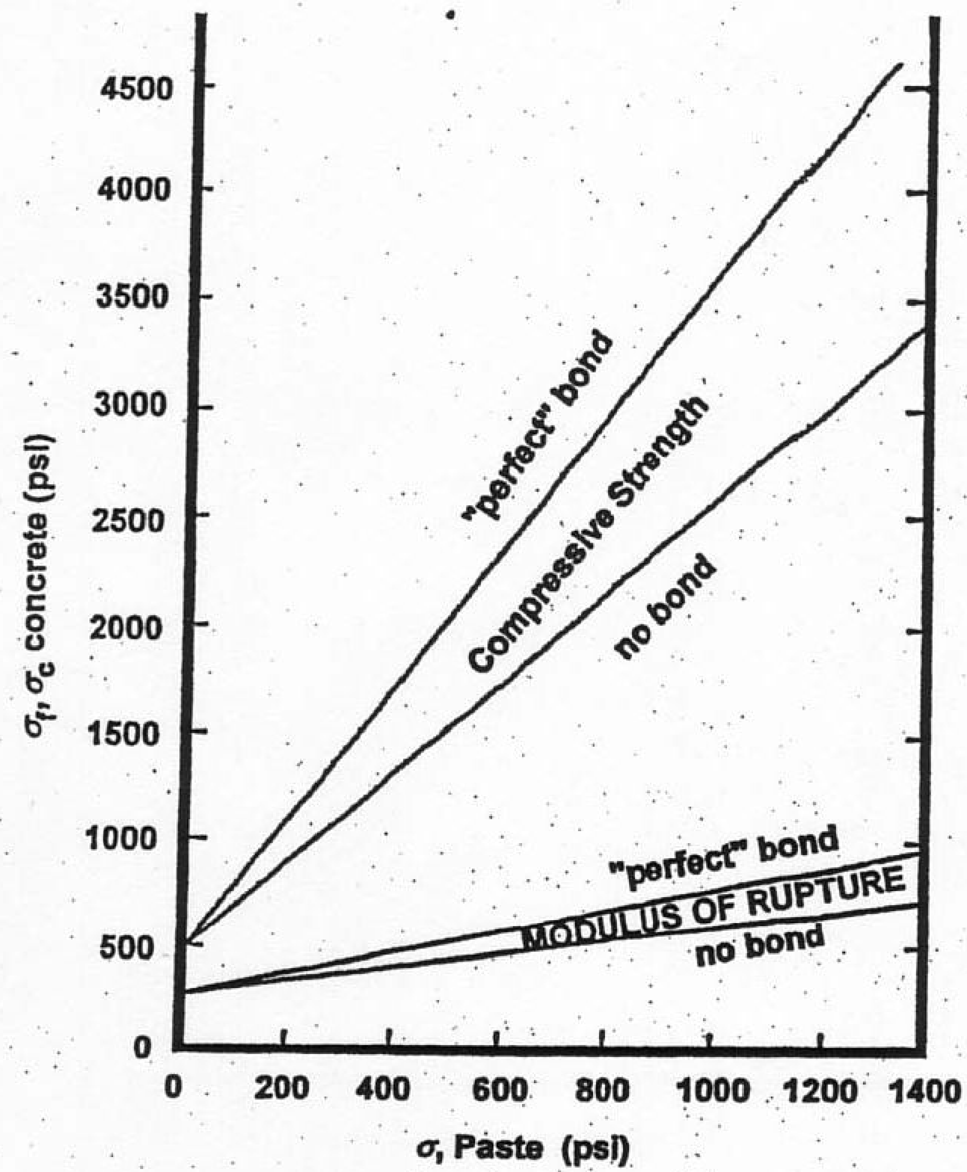


Figure 6.2. Effect of cement-aggregate bond strength on the compressive strength (σ_c) and flexural strength (σ_f) of concrete.[12]

Cont.

- There are number of practical ways in which the bond between the hcp and the aggregate can be improved.
- Addition of silica fume densifies the interfacial region and improves the paste aggregate bond.
- Less free water (i.e., bleeding water) at the interface
- A reduction in the size of the transition zone due to the pozzolanic reaction between Ca(OH)2 and silica fume
-
- The wall effect also results in higher porosity in the contact zone compared to the bulk cement paste.

1.3 LWA-cement paste interface

- The lightweight aggregates have a porous surface, due to this , some part of the binder will penetrate into the aggregate, which will subsequently decrease the internal bleeding water zone.
- The surface bleeding is due to a high permeability of unhydrated cement paste. A consequence of this phenomenon is laitance, which consist of a highly porous and weak film of mortar on the surface of hardened concrete.
- The phenomenon of internal bleeding is not well known. It is illustrated in Fig.6.3. The internal bleed water may contain fine particles of sand and cement, and gives rise to a porous cement paste matrix at the aggregate surface, a phenomenon similar to surface laitance.

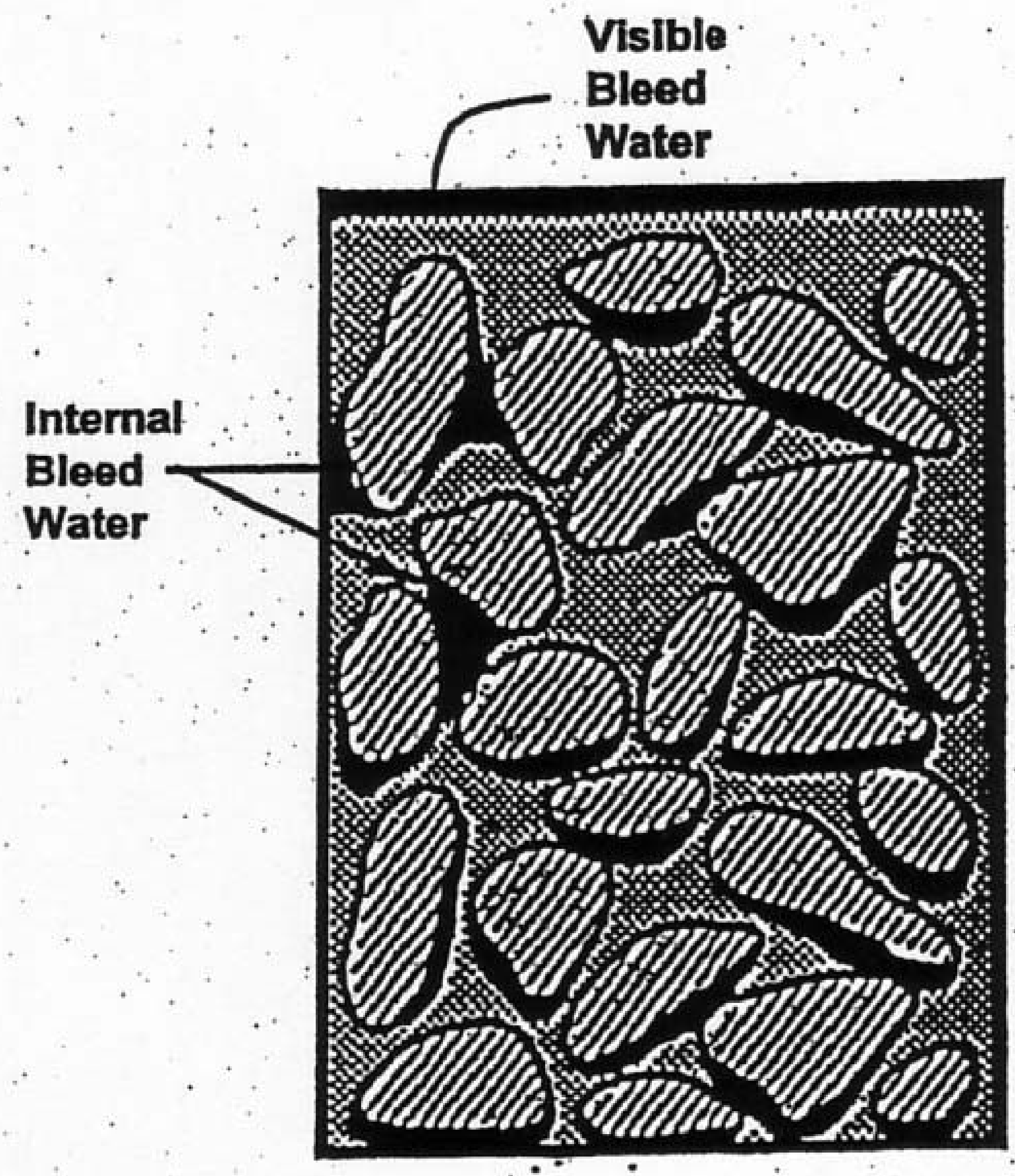


Figure 6.3. Schematic representation of bleeding in freshly-placed concrete.[14]

Cont.

- Fig.6.5 illustrates how the presence of fine mineral admixture particles (0.1um diameter) between two cement particles would effectively reduce the size of the channels flow.
- The chemical interaction of the mineral admixtures decrease the interfacial transition zone. It is illustrated in Fig.6.4. The bond between the aggregates will not be on the surface of the aggregates, as in the case of stone aggregates in regular concrete, but will move further inside the LWA.

2.0 Pore structure of LWA

- LWA are porous and have the ability to suction.
- There are two types of pores in the LWA: open and closed pores.
- Open pores are the pores that are interconnected and take part in the permeation, whereas the closed pores are sealed and not interconnected.
- The simple way to assess the interconnectivity of the pores is by measuring the water absorption property

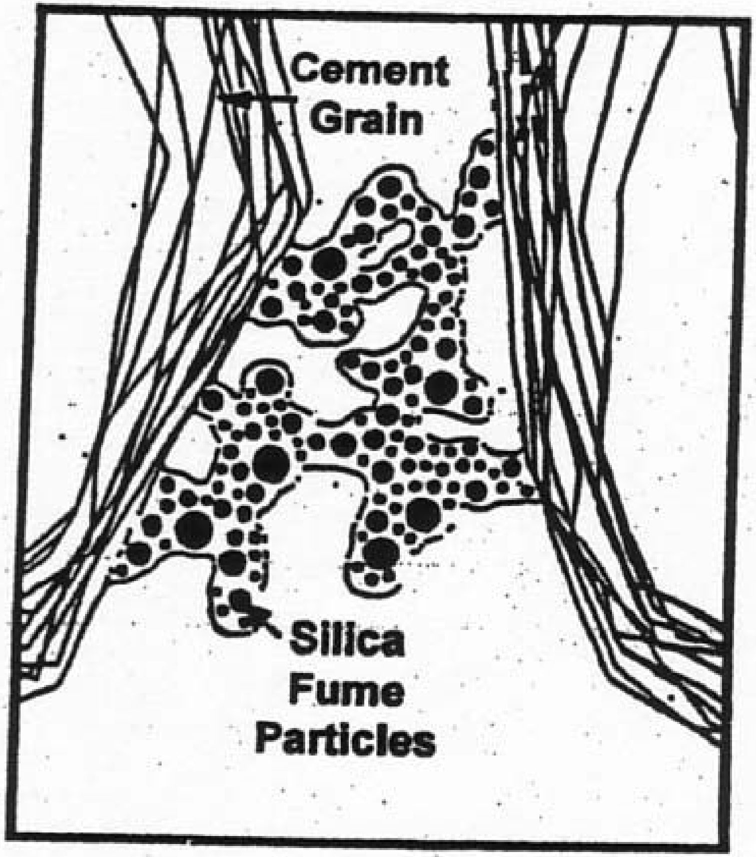
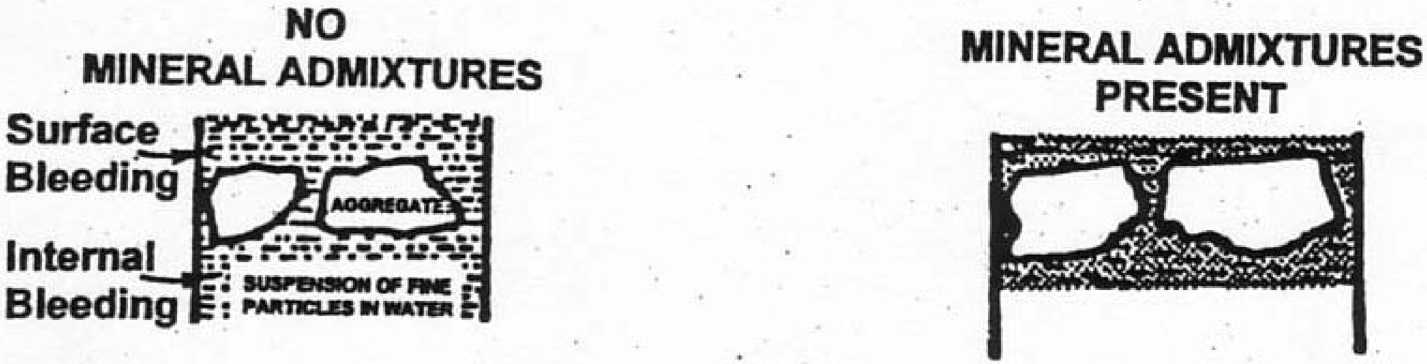
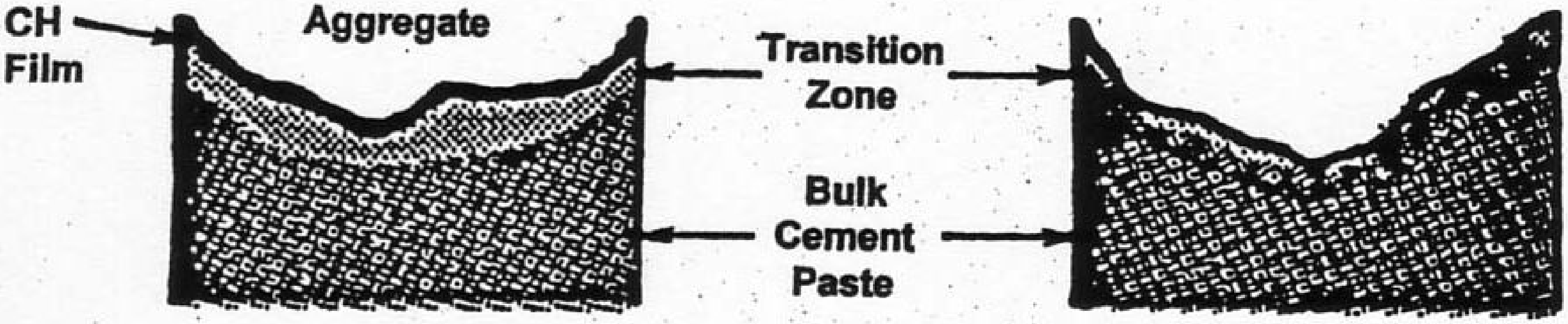


Figure 6.5. Schematic diagram representing blockage in channels of fluid flow by fine particles.[15]



Idealized representation of freshly compacted concrete, showing surface bleeding and internal bleeding effects



Idealized representation of the Transition Zone in Hardened Concrete

Figure 6.4. Schematic diagram representing reduction in the size and porosity of transition zone by addition of pozzolanic material.[14]

2.1 Water Absorption

- The connectivity of the pores in the aggregate is determined by immersing the aggregates in water for 24hours and later completely saturating them under vacuum.
- The difference between the water absorption thus measured will indicate the fraction of non-interconnected pores.

Table 6.1. Water Absorption of Lightweight Aggregates[16]

Aggregates	Initial moisture (% by wt)	Water absorption (24 h)	Water absorption under vacuum	Inter-connectivity (%)	Density of aggregate	
					Surface dried (kg/m³)	Wet (kg/m³)
Sw. Leca™	0.04	10.2	22.2	46.0	735	836
Liapor™ 5	0.21	16.1	22.6	71.2	911	1072
Liapor™ 6	0.08	17.1	21.5	79.5	1155	1326
Liapor™ 8	0.69	21.0	21.6	97.2	1535	1745

Interconnectivity ratio of water absorption after 24 hours and under vacuum. Water absorption is calculated on the percentage of dry mass

Table 6.2. Mix Proportion of LWA Concrete[21]

No.	Type of Aggregate	Cement (g)	Aggre-gate (g-)	Water (g)	W/C /est.	Particle Density g/cm^3
1	Liapor™ 8	600	274	202	0.3	1.37
2	Liapor™ 7	600	250	203	0.3	1.25
3	Liapor™ 6	600	214	206	0.3	1.07
4	H.S.S. Leca™	600	260	211	0.3	1.30
5	Lytag™	600	288	217	0.3	1.44

H.S.S.Leca™ - high strength Swedish Leca™.

3.0 Microstructure of the interfacial transition zone

- Microstructure is usually studied using a scanning electron microscope.
- For the LWA without a dense outer shell (Lytag), the cement paste may penetrate the surface pores, thereby providing a good mechanical interlocking after hardening between the aggregate and paste.
- It should be noted that the density and thickness of the outer layer of LWA may vary from one particle to another, and even from one area to another on the same particle.
- For the increasing density of the outer layer of LWA, the nature of the interfacial transition zone becomes more similar to that observed for the normal concrete.

3.1 Microstructure of old concrete

- SEM photographs of concrete from some mature bridge decks have shown that the LWAs were extremely well bonded to the cement paste matrix.
- Khokhorin's results are summarized as follows:
- "On the whole one should note that the quality as defined by cohesion, density, and strength of the contact zone of the concrete based upon porous aggregates is better than that of the concrete zone of normal concrete based on dense aggregate."

3.2 Elastic compatibility

- Cracks are often found at the interface between the aggregate and the concrete paste. In the case of LWAC, one does not see them.
- The primary reason for the lack of bond cracks may be due to the similarity of elastic stiffness of the LWA and mortar fraction.
- The stress concentration is decreased.

- Its practical implication is that the LWAC tends to have a lower permeability to gases and aggressive liquid than does normal concrete when subjected to load.
- Nishi reported that for both fresh and sea water test programs, Japanese structural LWAC demonstrated greater resistance to penetration than the normal concrete.
- They have suggested that there is a probability a formation of a coating layer of dense paste.

3.3 Pozzolanic interaction

- A LWA has a glassy surface, which is formed during sintering process. This phase is amorphous and potentially reactive. This phase interacts chemically with the $Ca(OH)_2$ produced during the hydration of cement.
- (So, some researchers are afraid of AAR.)

4.0 Interrelation of micro-structure and the strength of LWAC

- Careful micro-structural examination reveals the importance of the external and internal structure of LWAs in the development of paste-aggregate bond, the effect of water cement ratio, and mineral admixtures on the porosity of paste.

5.0 Concluding remarks

- The paste-aggregate bonding is dependent on the nature of the external shell of the aggregate.
- Mechanical interlocking plays an important role in strengthening the interface.
- Absence of the oriented Ca(OH)2 is related to the absorption of water by LWA.
- There is some micro-structural evidence of pozzolanic activity of LWA, which is possible due to the chemical reaction.
- About 10% addition of silica fume helps to improve the early strength in some cases, whereas positive evidence of the latent hydraulicity of slag was noted in the concrete containing 30%.

11. Applications of LWAC

1.0 Introduction

- LWAC has been used since the ancient periods.
- The fact that some of the structures are still in good condition speaks about concrete's durability.
- 2.0 LWAC and thermal insulation
- The thermal resistance of LWAC is up to 6 times that of normal weight concrete.
- In some designs, when the LWAC is used for exterior wall, a substantial reduction in heating cost results.
- 3.0 Horticultural applications (園芸)
- 4.0 Ship building
- 5.0 Building industry
- 6.0 Bridges

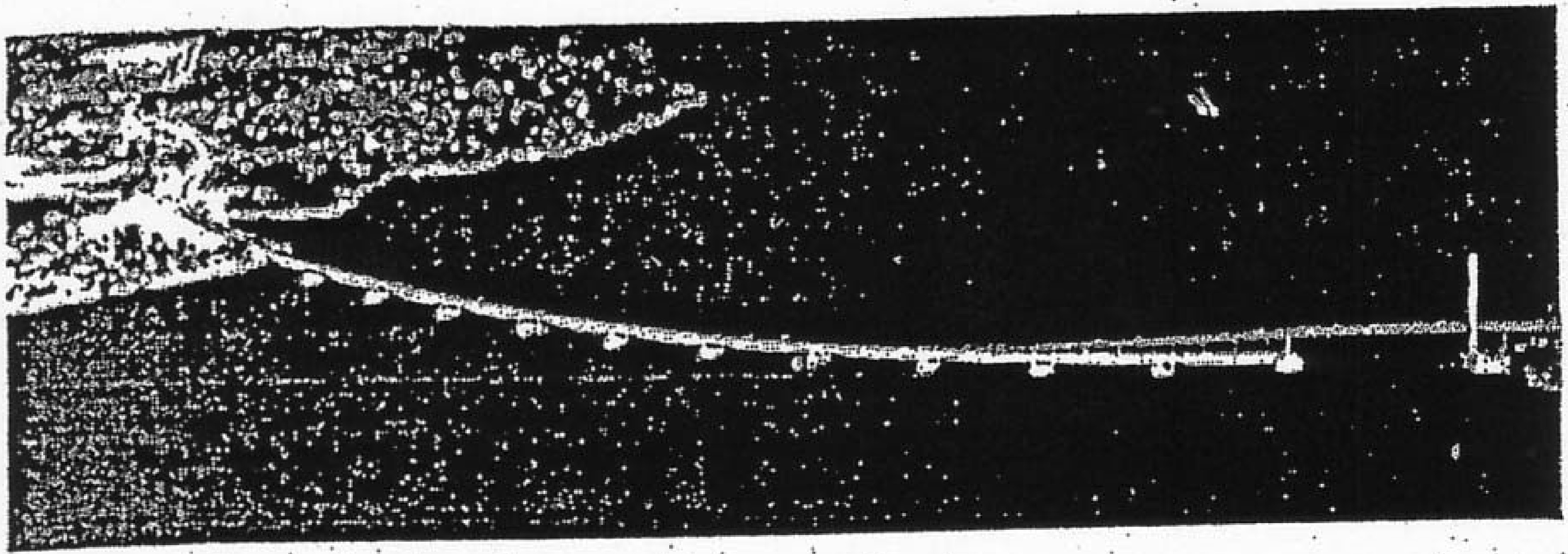


Figure 11.9. The Nordhordlands Bridge with floating bridge to the left and the cable-stayed bridge on the right-hand side. The total length is 1615 m.[21]

Table 11.1. Offshore Constructions in Norway[21]

Name	Types of Construction	Grade	Density kg/m^3	Built	LWAC Volume m^3
Snorre foundation	Templates	LC60	1900	1990–91	1,100
Troll GBS	Gravity base	LC75	2250	1992–95	60,000
Heidrun TLP	Tension leg	LC60	1950	1993–95	65,000
Troll West floater	Catenary anchored	LC75	2250	1993–95	20,000

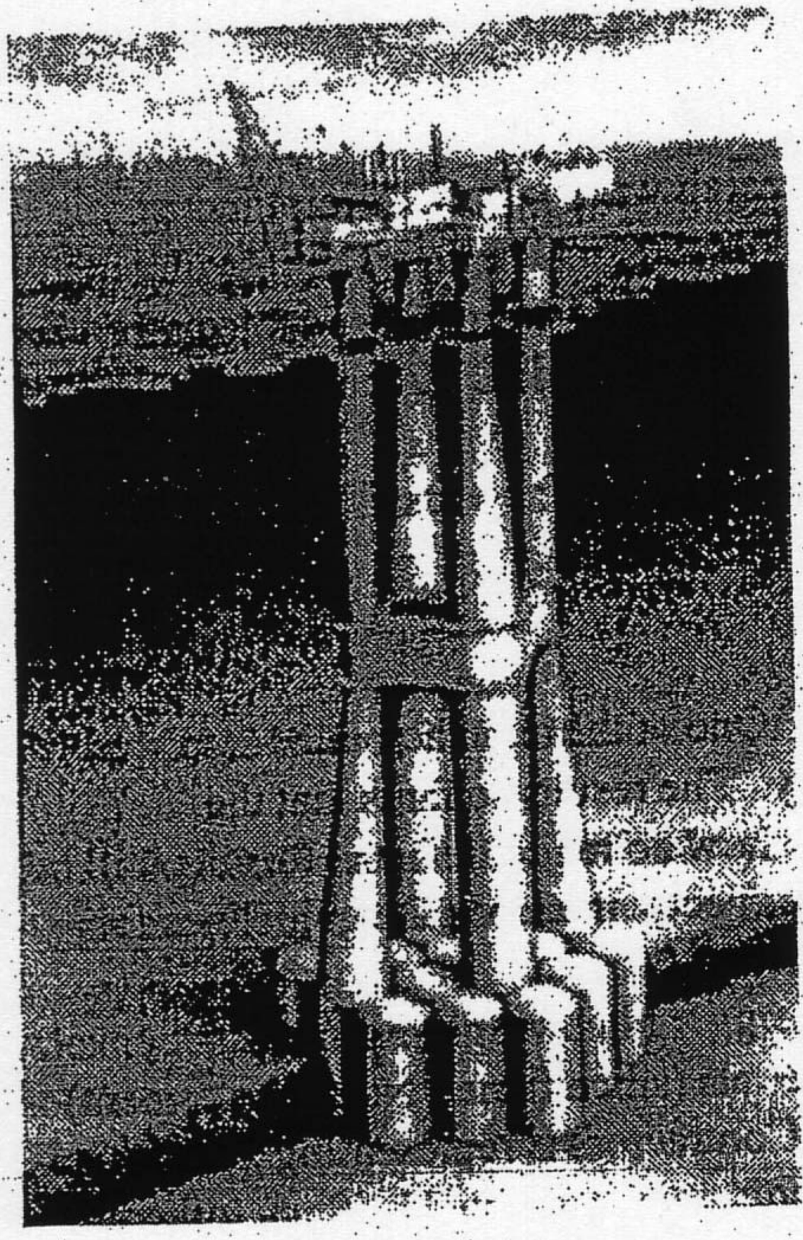


Figure 11.10. The 370 m tall Troll GBS partly made of LWAC with a density of 2250 kg/m^3 and strength LC75.[21]

7.0 Advantages and disadvantages

7.1 Advantages

- Purity of aggregate: man-made
- Lower dead load
- Better physical properties: lower modulus, lower coefficient of thermal expansion, easier drilling
- Improved durability: This is because of the reduced likelihood of shrinkage and early thermal cracking, lower permeability and etc.
- Environmental problems: The benefit can be significant of industrial waste products are used to manufacture LWA.
- Offshore Platforms construction: additional buoyancy, better cracking behavior, lower permeability, improved freeze-thaw resistance, savings on transport, etc.
- Demolition

7.2 Disadvantages

- Reduced resistance to locally concentrated loads
- More brittle
- Greater care is required in controlling water content, mixing, and supervision.
- Special measures for pumping concrete

- The end