IMPACT OF DROPPED OBJECTS ON LIGHTWEIGHT CONCRETE

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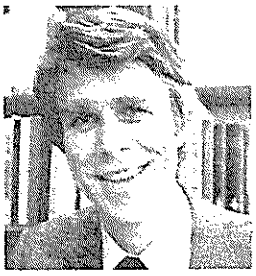

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ABSTRACT

Impact tests have been carried out to investigate the impact of dropped objects on lightweight aggregate concrete. The local damage and penetration, impact time and impact force and their dependence on material properties, mass, velocity and geometric shape of the falling object have been studied. Based on the test results, simplified analytical models have been proved.

Key words: Concrete, lightweight aggregate concrete, impact, offshore structures

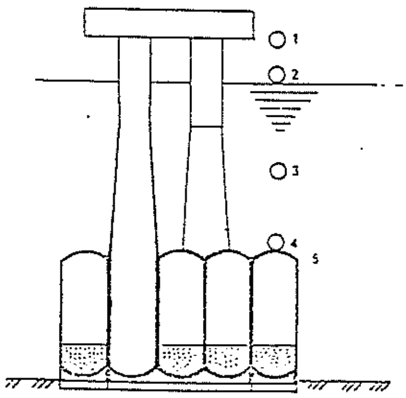
1. INTRODUCTION

On offshore production platforms there will be a possibility that falling objects from the platform deck can strike structural elements below and cause damage (figure 1). Experience has shown that damage caused by dropping objects can really happen and such cases have therefore to be considered in design. Problems related to determination of impact loads, dynamic response, flexural and punching capacity as well as impact on a lightweight concrete have been examined in previous studies [1][2]. To examine the local damage and the effect of a lightweight concrete protection cover on structural elements, impact tests with dropped objects have been carried out at Cement and Concrete Research Institute, Trondheim, ordered by Norwegian Contractors. The experimental work aimed to extend the knowledge of energy absorption, local damage and penetration of falling objects on normal density and lightweight concrete. The impact material properties of the materials mentioned, the influence of the shape and the velocity of the falling object on the impact load and the impact time have been investigated. These data may be of importance in a dynamic response analysis and in a safety evaluation of accidental loads. The present paper gives a brief summary of the work reported in [3] and [4].

2. TEST PROGRAMME AND TEST ARRANGEMENTS

2.1 Test programme

The impact tests have been carried out in three steps:



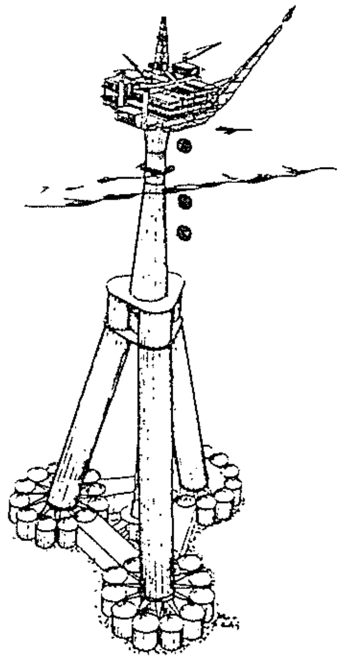


Figure 1.1. Dropped objects on Condeep platforms.

- *Series I* : 18 test specimens with 71 impact tests examining the local damage, penetration, impact force and impact time caused by falling objects on normal offshore concrete and lightweight "LECA"-concrete. The impact velocity ranged between v = 3 and 7.6 m/s.
- *Series II* : 9 impact tests and 3 static tests on lightweight Leca concrete test specimens. The impact velocity ranged between v = 4.2 and 13.4 m/s.
- *Series III* : 16 test specimens with 19 impact tests and 11 static tests on lightweight Liapor concrete test specimens.

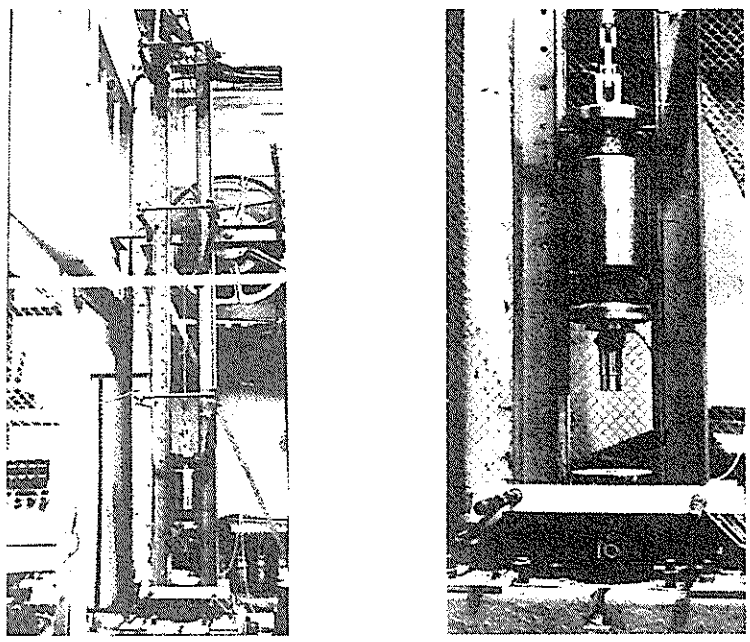
In series I, a falling object with the mass of 108.4 kg was dropped from different heights of 0.5 - 3.0 m, which corresponds to impact velocities of 3.13 - 7.67 m/s. The front of the mass was either cylindrical, spherical or conical, in order to investigate the effect of the shape of the object. The impact force, impact time, penetrating depth and local damage due to spalling were recorded. Most of the tests were carried out twice with the same test conditions, in order to examine the scatter in the test results. A distinction was also made between the impact nos 1, 2 and 3 at the same spot. Primarily, the impact no 1 was of importance. Using the test specimens on two sides and repeated testing, the number of impact tests on which the test results are based is 71.

The test series no II included 9 impact tests and, in addition, 3 static tests on lightweight Leca concrete. The impact tests aimed to study the influence of higher impact velocities on the penetration, impact force and impact time. The mass of the falling object was 42 kg and only the cylindrical head was used.

The test series III is an extension of test series II and included 19 impact tests and 11 static tests on lightweight Liapor concrete. The static tests should give information about the load-penetration relationship of a cylindrical head Ø 50 mm, a knife head of 25 x 150 mm and a large cylinder Ø 170 mm (figure 2.1). The impact tests included testing of impact at different velocities. The influence of confinement of the concrete was examined.

2.2 Test equipment and instrumentation

A test rig as shown in figure 2.1 was used. In test series I a falling mass was dropped from different heights, limited to velocities of 7.6 m/s, which corresponds to velocities of a dropped object like a mud pump. Dropped objects like riser pipes differ from the mud pumps in having less mass and higher impact velocities. To handle higher velocities, a catapult mechanism with springs was therefore used in the test series II and III (V_{max} = 13.4 m/s).



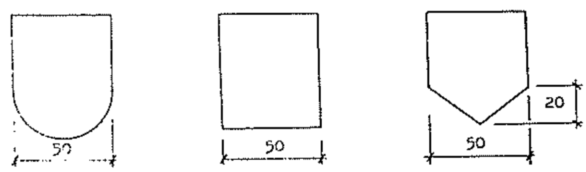


Figure 2.1. Test arrangements and heads of falling objects.

The instrumentation set up, as used in the test series II and III, is shown in figure 2.2. The impact head is instrumented with strain gauges and gives the possibility to determine the impact force and impact time, i.e. the impulse of the falling object.

The static tests were performed as shown in figure 2.3. The load-penetration relationship was recorded. In general, the load-velocity was 0.2 kN/sec. The heads of the objects tested are shown in figure 2.3.

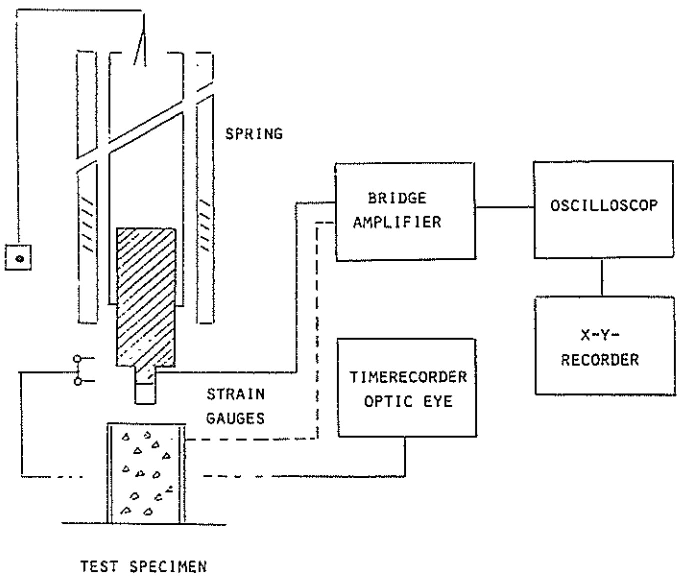


Figure 2.2. Instrumentation.

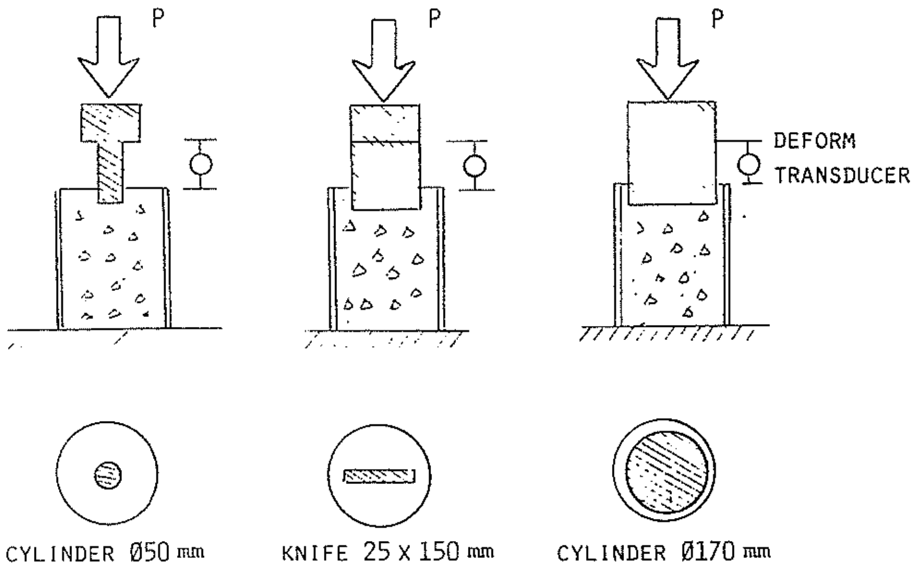


Figure 2.3. Static tests.

2.3 Test specimens

The test specimens were grouted in steel tubes as shown in figure 2.4. The steel tubes serve as confinement of the concrete specimens. These confined specimens represent a local concrete area of a larger structural concrete element.

18 test specimens were made in test series I. 12 of the test elements were made of concrete of the quality normally used in offshore structures. The concrete quality properties are summarized in table 2.5. The additional 6 test specimens were made with a 50, resp. 100 mm thick lightweight concrete protection cover as shown in figure 2.4.

The test elements of the test series II were made of pure lightweight Leca concrete while the test series III was performed with lightweight Liapor concrete. The material properties are summarized in table 2.5. One test specimen was instrumented on the steel ring to clarify the influence of the confinement (spec. no 6) while two test specimens were tested without steel ring, also to examine the influence of confinement (spec. nos 15 & 16).

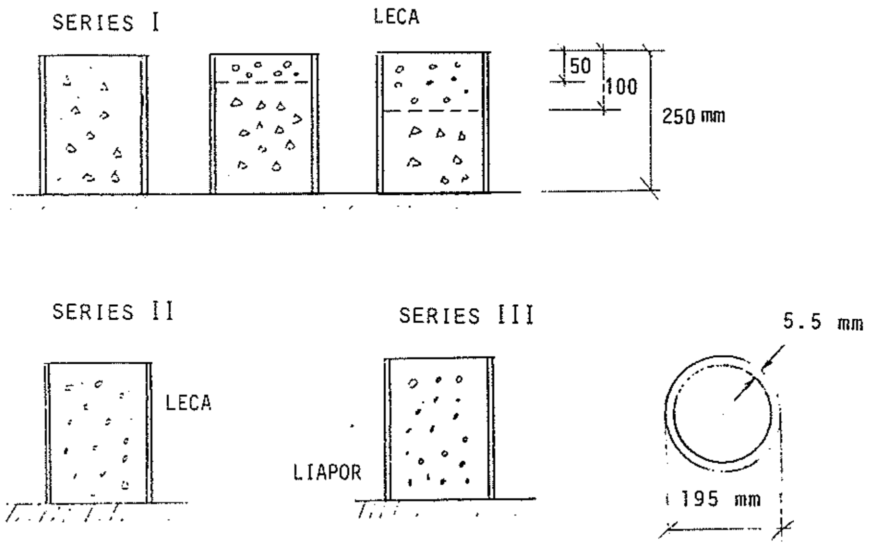


Figure 2.4. Test specimens.

	Series I		Series II	Series III	Dim.
	NC	LC	LC	LC	
CUBE STRENGTH 28 days Test date	73.4 66.0	6.2 5.0	- 4.0	10.3 10.4	N/mm² "
SPLITTING STRENGTH	3.9	0.76	-	1.7	N/mm²
E-MODULUS	31850	8125	-	7362	N/mm²

Table 2.5. Material properties.

3. TEST RESULTS

The test results are presented in the figures 3.1 - 3.10 and may be summarized as:

- The tests have shown that penetration, impact time and impact forces strongly depend on the concrete material properties, as well as the mass, velocity and geometric shape of the falling object (figure 3.1).
- Ligthweight concrete as protection cover on structural concrete clearly influences the impact time and the impact force (figure 3.2). It leads to the prolongation of the impact time and to a smaller impact force. The reduction of the impact force may be considerable and depends on the geometric shape of the object (figures 3.3 and 3.4).
- The local damage on normal structural concrete turns out like penetration and spalling of concrete. Using lightweight concrete, the local damage is limited to a local "crater" which approximately corresponds to the geometry of the falling object (figure 3.5).
- Under repeated loading, the local penetration decreases whilst the impact load increases. In the case of structural normal dencity concrete (NC), a larger spalling occurs under repeated loading. For lightweight concrete, (LC), a consolidation of the material occurs. It leads to higher impact forces at repeated loading.
- The penetration during impact loading on concrete materials can be estimated by considering the transmission of kinetic energy into plastic strain energy.
- The relationship between the penetrated volume of concrete and the kinetic energy of the falling object, assuming a crushing strength of concrete, may be expressed as

$$V_c = \frac{1}{2} \frac{M v_o^2}{\bar{y}_s}$$

where V_c = volume of penetrated area, M = mass of falling object, v_o = velocity of falling object and $\bar{y}_s$ = "crushing" strength of concrete.

For a cylinder-shaped object, the penetration volume is $V = 1/4 \cdot \pi \cdot D^2 x_o$ where D = diameter of cylinder and x_o = penetration depth.

Then:

$$x_o = 2 \frac{M}{\bar{y}_s} \frac{v_o^2}{\pi \cdot D^2}$$

- The material property called "crushing strength" or "impact strength", $\bar{y}_s$, is of importance in an analytical investigation of the penetration, the impact time and the impact forces. This material property has to be determined experimentally. For concrete materials, the concrete cube strength will be used as reference. The impact strength may be defined as

$$\bar{y}_s = k_s \cdot f_{cj}$$

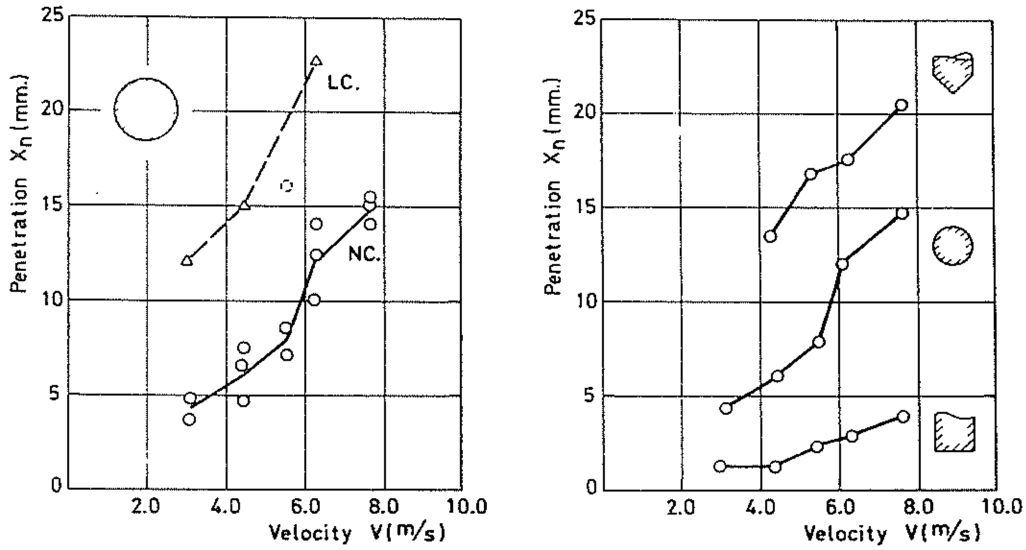


Figure 3.1. Relationship between penetration depth and velocity of falling object. Influence of shape of object and lightweight concrete. Test series I.

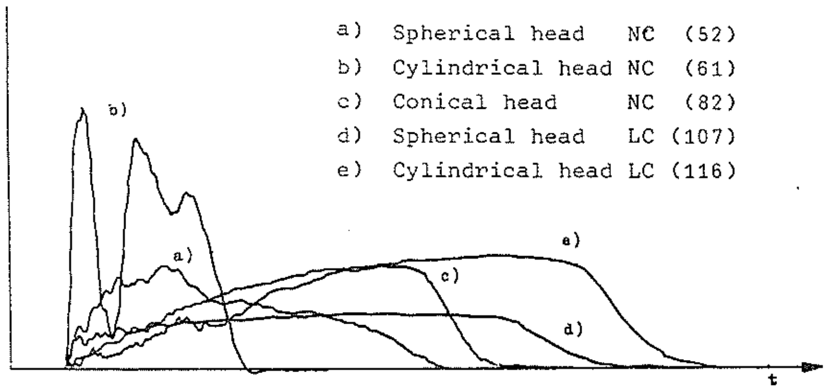


Figure 3.2. Impact force-time relationship. Test series I.

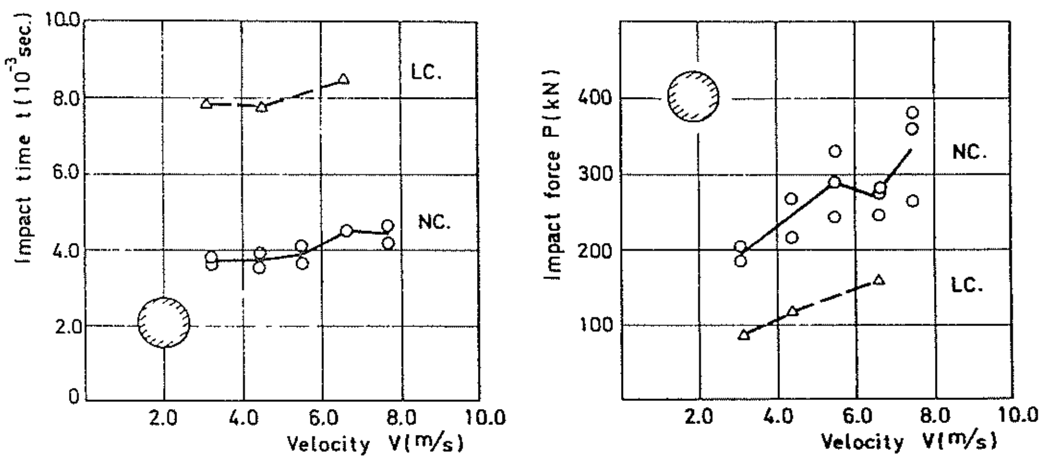
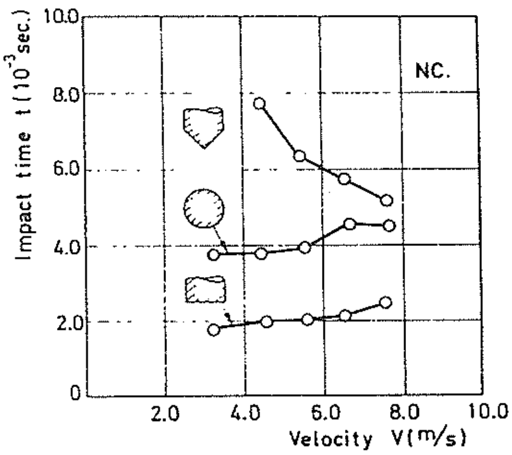


Figure 3.3. Impact time and impact force. Spherical head, normal and lightweight concrete. Test series I.



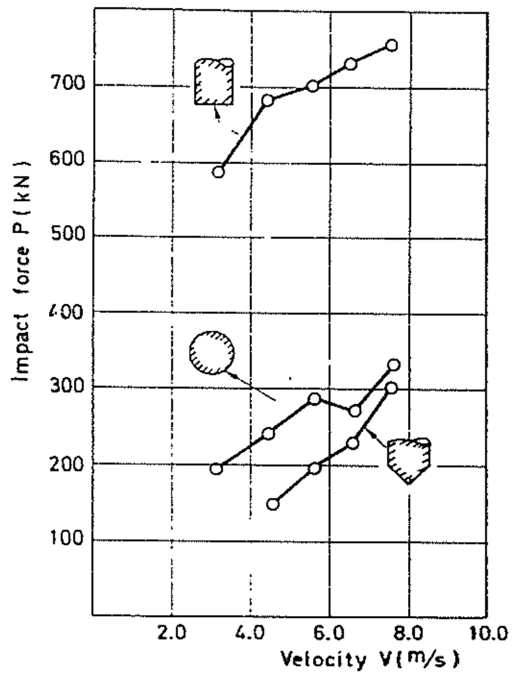
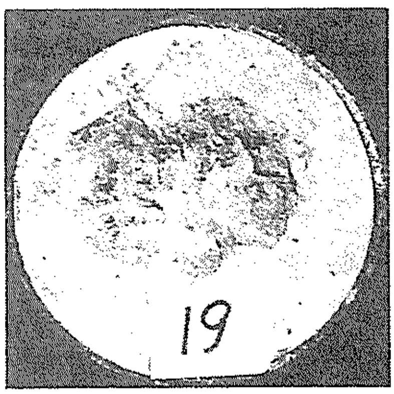


Figure 3.4.
Impact time and impact force.
Different impact heads. Test series I.



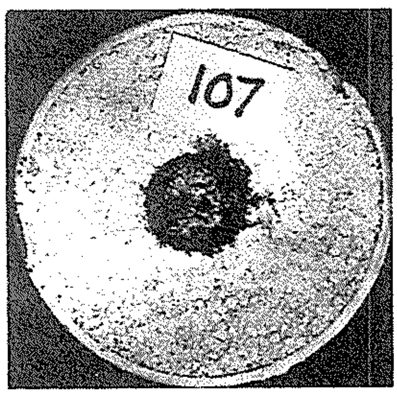
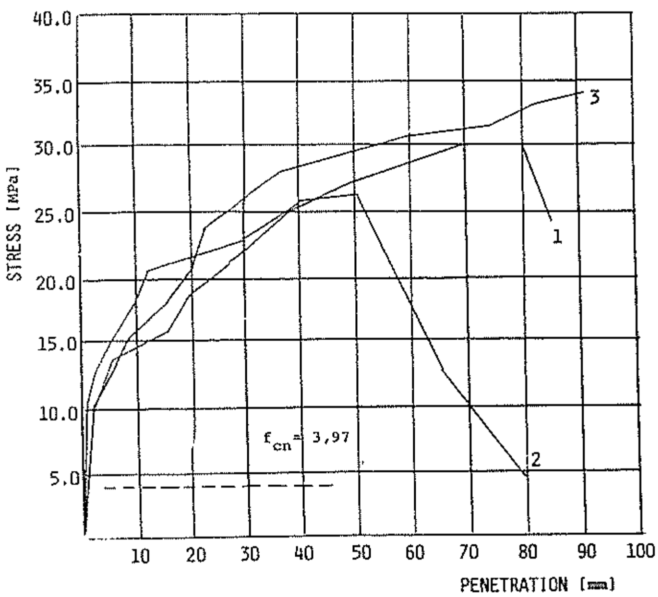


Figure 3.5. Local damage of NC (19) and LC (107). Spherical head, v = 6.26 m, m = 108.4 kg. Test series I.



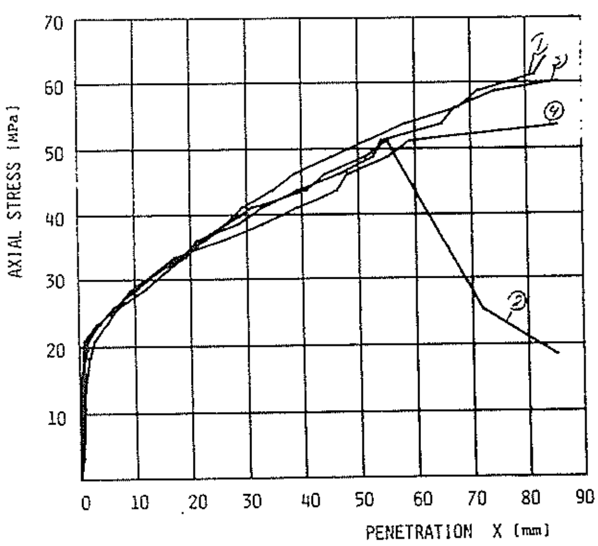


Figure 3.6. Stress-penetration relationship of Leca and Liapor. Cylindrical head. Test series I and II.

where f_{cj} = concrete cube strength
k_s = coefficient

- For normal structural concrete a k_s-value k_s^{NC} = 5.0 was recommended [3].
- For lightweight concrete, static and dynamic tests were performed to determine the k_s-value.
- The static tests confirmed a crushing strength of lightweight concrete of 5-7 times the corresponding cube strength of the material (figure 3.6). The crushing strength may only be obtained at constrained conditions. Constrained conditions may be fulfilled when a local area of a larger structural element is exposed to loading.

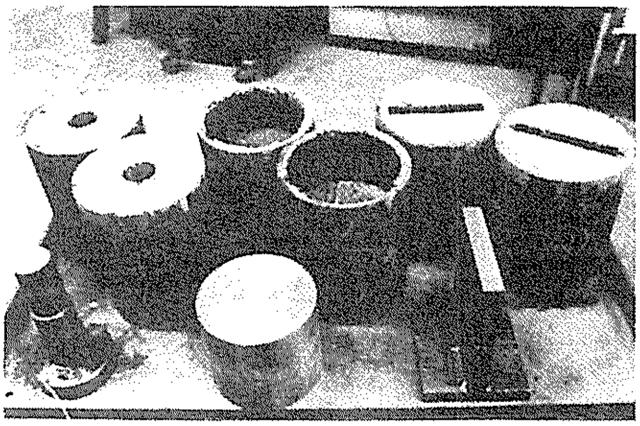


Figure 3.7. General view of test specimens and "heads". Static tests of series III.

- The static tests confirmed a "compressibility", i.e. ability to volumetric change, of 30-40% for lightweight concrete (Liapor) (figure 3.7.).
- The dynamic tests on lightweight concrete showed that the impact peak stress may exceed the static crushing strength. Furthermore, the impact crushing strength was found to be dependent on the impact velocity. Confinement and consolidation properties have to be considered.
- Impact test results of the test series III are summarized in table 3.8 while examples of recordings from impact tests are shown in figure 3.9. In figure 3.10 the relationship between the penetration and the kinetic energy is presented. An approximate linear relationship was stated. The penetration and absorbed strain energy relationship during static tests is also plotted in the same figure to establish the relationship between strain energy of static tests and kinetic energy of impact tests with respect to penetration.
- Analytical investigation of the test results leads to a recommended impact strength assumption for lightweight Liapor concrete of:

$$\bar{y}_s = k_s \cdot f_{cj} = \alpha_s \cdot f_{cj} \cdot V^{2/3}$$

where V = velocity of dropped object [m/s]
f_{cj} = cube strength of material

The α-value is dependent on the consolidation properties of the material (i.e. compressibility, confinement, thickness of cover). The α-value can be evaluated through static tests comparing absorption of strain energy. The tests performed give reference values Leca: α_s = 1.67, Liapor: α_s = 0.90.

v	HEAD	m	x_o	t	P_{max}	σ_{max}	P_{mean}	σ_{mean}	SPEC. NO	TEST NO	SIDE
6.1		42.0	12.4	5.1	75.6	38.5	59.2	30.2	3	5	1
6.1		"	11.2	4.6	83.8	42.7	67.9	34.6	3	6	2
6.1		"	8.1	4.5	98.8	50.3	69.1	35.2	3	6II	2
6.2		"	11.2	4.7	90.5	46.1	62.6	31.9	4	7	1
6.1	CYL	"	10.5	4.5	99.2	50.5	67.6	34.5	4	8	2
6.5		108.0	29.6	10.6	115.4	58.8	89.6	43.1	7	13	1
6.3		"	25.4	9.7	119.2	60.7	89.7	45.7	7	14	2
6.2		"	27.3	10.3	113.8	58.0	83.1	42.3	8	15	1
6.2		"	27.6	10.2	115.6	58.9	88.5	45.1	8	16	2
6.1	CYL	"	18.3	8.5	133.9	68.2	100.2	51.1	8	16II	2
12.9		42.0	37.1	6.6	123.6	63.0	89.2	45.5	5	9	1
12.9		"	35.2	6.4	123.4	62.9	94.2	48.0	5	10	2
13.0		"	24.5	5.4	145.0	73.9	109.0	92.3	5	10II	2
-		"	31.1	6.3	125.2	63.8	92.3	47.0	6	11	1
13.1	CYL	"	36.2	6.5	119.0	60.6	91.7	46.7	6	12	2
3.1		42.0	3.8	3.6	67.0	34.1	48.6	24.8	15	29	1
6.2		"	22.0	6.2	97.7	49.8	50.1	25.5	15	30	2
6.1		"	11.0	4.8	85.3	43.5	65.6	33.4	16	31	1
(7.0)	CYL	"	16.6	-	-	-	-	-	16	32	2
		kg	mm	m/sec	kN	MPa	kN	MPa			

Table 3.8. Test results of impact tests. Test series III.

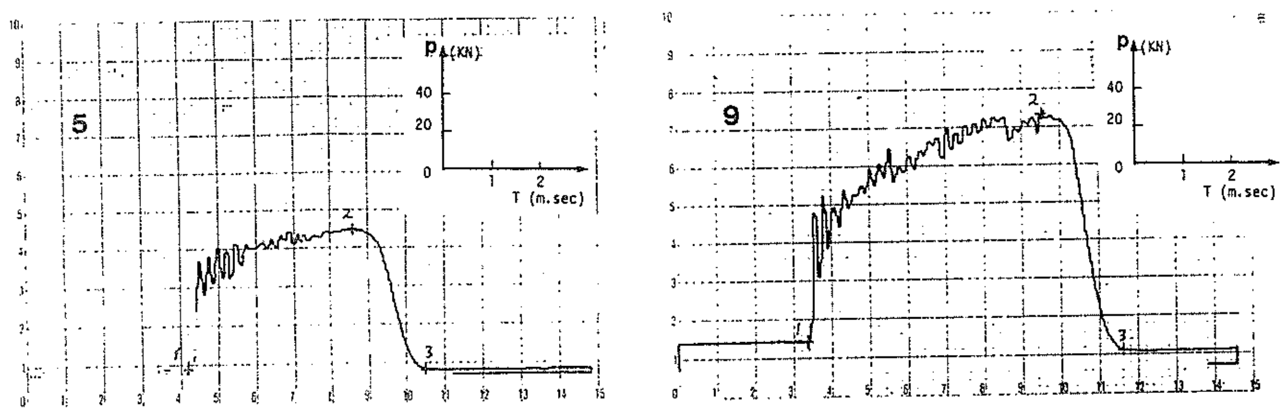


Figure 3.9. Recordings of impact tests nos 5 and 9.

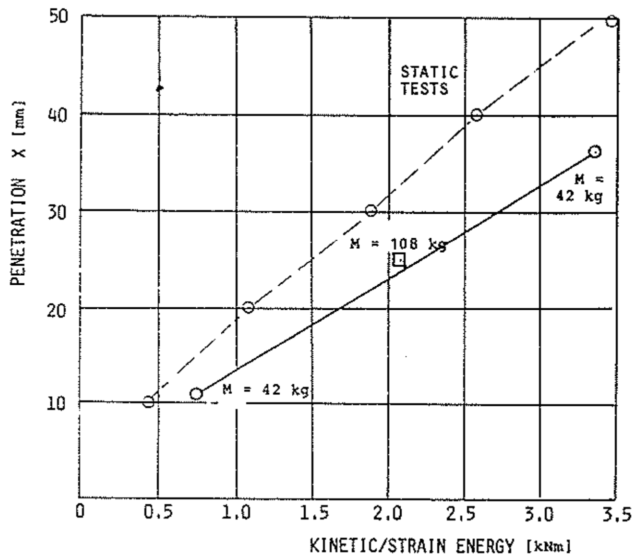


Figure 3.10. Relationship between penetration and kinetic energy. Absorbed strain energy during static tests. Test series III.

. Based on the test results and the recommended material properties, the penetration depth x_o of falling objects can be estimated.

. Knowing the penetration depth and assuming a variation of the velocity of the object (linear) during impact, the impact time can be determined:

$$t_d = \frac{2x_o}{v_o}$$

. The impact force can be determined on the basis of the impulse law when the mass and velocity of the falling object are known. The impact time determined on the basis of the penetration has to be taken into account.

. The impact load can be deduced on the basis of the impulse law

$$I = M \cdot V_o = \int P(t)dt = C \cdot P_o t_d$$

where I = impulse
m, V = mass, resp, velocity of the falling object
P_o = maximum impact force
t_d = impact time.

The constant C depends on the shape of the impulse. In the case of triangle, trapeze, or rectangular-shaped impulses the C-values are $C_1 = 1/1$, $C_2 = 2/3$ and $C_3 = 1$. Then

$$P_o = \frac{M \cdot V}{C \cdot t_d}$$

- The impact force determined in this way may serve as input in a dynamic response analysis of structural elements exposed to impact loads.
- Comparison between analytical and experimental results gives information to judge the applicability of the proposed analytical method, and to determine possible load coefficients which have to be used in design practice.

- The test performed has been carried out on small test specimens. The test results have, however, clarified impact material properties and demonstrated favourable characteristics of a lightweight concrete as protection cover. The test results and the proposed analytical method to determine the impact load and impact time may serve as basis for a dynamic impact response analysis of structural elements with lightweight concrete protection cover.

ACKNOWLEDGEMENTS

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