MECHANICAL PROPERTIES OF IMMOBILIZED INTERMEDIATE LEVEL WASTES

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Abstract

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The paper describes a programme of work in which the mechanical properties of immobilized waste forms were evaluated and related to the impact performance of immobilized waste packages. The waste forms under investigation were Magnox cladding (swarf) and Magnox sludge (corrosion products of Magnox swarf) immobilized in cement, ion exchange resins immobilized in a polymer and a control material (cement grout) to provide a benchmark against which the properties of the chosen waste forms could be compared and contrasted. The material properties evaluated were limited to those of direct relevance to impact studies, namely the elastic moduli, uniaxial compressive and tensile strengths, ductility, triaxial failure criteria and behaviour under high rates of strain. During most of the programme, conventional laboratory test machines were employed, although some minor modifications were carried out where necessary. Results are presented for the above range of properties for each material and comments are made on the levels of confidence associated with the data and the limits of their applicability. These properties were used to gain an understanding of the impact behaviour of 500 L drums full of the same immobilized wastes. A programme of drop tests on stainless steel sheet metal drums was carried out at drop heights of between 9 and 36 m and in three different drop attitudes. All drop tests were instrumented with accelerometers. Drum deformations were related to the measured mechanical properties of the immobilized wastes. The drop tests were supplemented by a programme of non-linear, finite-element analysis, points of similarity and discrepancy have been highlighted and some guidelines for estimating the impact strength of immobilized waste packages are put forward.

1. INTRODUCTION

The work described in this paper is part of a larger programme being carried out by UK Nirex Limited directed towards the safe handling and transport of immobilized intermediate level radioactive wastes (ILW). These wastes will be immobilized in 500 litre drums using a cement or polymer matrix. The drums will be transported to the repository as a group of four in a handling frame within reusable transport containers. Further background and details of some of the waste streams can be found in another paper at this conference [1].

2. OBJECTIVES

The objective of this work was to develop a methodology by which the impact performance of different immobilized waste drums might be investigated without necessarily having to repeat large numbers of tests each time. To this end, a programme of materials tests and drum drop tests supplemented by finite element analysis was carried out having the following specific objectives.

i) To obtain basic data on the mechanical properties of selected immobilized wastes using relatively simple laboratory tests.

ii) To investigate the impact behaviour of immobilized waste drums by means of a series of full-scale drop tests.

iii) To relate the behaviour of the drums in the drop tests to the mechanical properties measured in the laboratory.

iv) To carry out sufficient finite element analysis of a drum under impact to provide an understanding of the results observed in the drop tests.

v) To provide guidance on impact performance of waste packages using laboratory test data.

3. PROGRAMME OF WORK

3.1 Selection of Waste forms

There are approximately 80 different waste streams in the UK. As a result it was necessary to select a small number of materials for examination, with the intention that any work done on these would provide a methodology which could then be applied to other materials at a later date.

The materials chosen were:-

i) Magnox sludge, immobilized in a matrix of blast furnace slag and ordinary portland cement (BFS/OPC)

ii) Magnox swarf, immobilized in BFS/OPC

iii) Ion Exchange Resin, immobilized in a water-extended vinyl ester resin (by Dow Chemicals Ltd)

iv) An inexpensive control material, consisting of a cement/China clay grout.

The curing time for Magnox swarf and Sludge was 90 days, for grout it was 28 days, and for Dow Polymer it was a few days. The waste forms were prepared by mixing and curing in 500 litre drums. Separate drums were filled for materials tests samples and the drum drop tests.

3.2 Materials Tests

Only those mechanical properties which are of interest in impact studies were evaluated. Samples for testing were obtained by coring from the drums using a conventional rotary core cutter. The cores were 50 and 100mm in diameter. The properties selected for study were:

1. Density
2. Static compressive strength (Unconfined)
3. Static tensile strength (unconfined)
4. Static Young's modulus
5. Static Poisson's ratio
6. Static triaxial strength (confined)
7. Dynamic compressive and tensile strength (unconfined)
8. Dynamic Young's modulus
9. Dynamic Poisson's ratio

Properties 1 to 5 are parameters which are frequently required for engineering purposes and are easy to measure. The appropriate equipment is readily available and plenty of previous expertise exists. The same is not true for properties 6 and 7 which are more difficult and much less frequently investigated. Properties 8 and 9 are not so commonly measured as properties 1-5, but they are not particularly difficult to obtain.

TABLE I. DROP TEST PARTICULARS

TEST No.	DRUM CONTENTS	IMPACT ATTITUDE	DROP HEIGHT	TOLERANCE ON ATTITUDE
1	Grout	Bottom Edge	9m	±2°
2	Grout	Axis horizontal	9m	±1°
3	Grout	Axis Vertical	36m	±1°
4	Dow	Bottom Edge	9m	±2°
5	Swarf	Bottom Edge	9m	±2°
6	Sludge	Bottom Edge	9m	±2°
7	Sludge	Axis Vertical	36m	±1°
8	Sludge	Bottom Edge	9m	±2°

3.3 Drum Drop Tests

A series of 8 drop tests were carried out on full-size drums filled with immobilized waste, in three different impact attitudes. TABLE I shows the particulars of the drop tests and FIG 1 shows the impact attitudes. The drums were dropped onto an IAEA unyielding target, using a guidance system to ensure accuracy of impact attitude.

The drums were manufactured from stainless steel sheet, grade 316L. The thickness of the skin was 3.25mm in the lid, 1.6mm in the sides and 2.6mm in the bottom. Fabrication details were kept as simple as possible to minimise the effect of local design features (FIG 2).

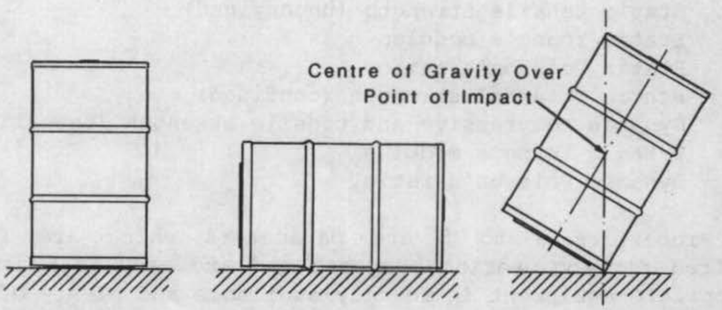

FIG. 1. *Drum drop test attitudes.*

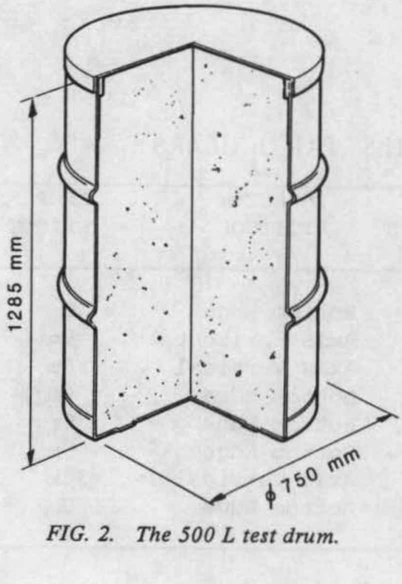

FIG. 2. *The 500 L test drum.*

4. MATERIALS TESTS

4.1 Description

The tests were planned so that non-destructive testing on any sample preceded the destructive testing and, where possible, one test was used to determine more than one property.

Density was obtained by simply measuring and weighing the samples. The static Young's Modulus, Poisson's ratios and compressive strength were obtained from compressive tests on 200mm long, 100mm diameter cored cylinders, instrumented with two circumferential and two longitudinal strain gauges.

Static tensile strength was measured using the Brazil Cylinder Splitting Test. The 45mm thick disc used for the test was prepared by cutting a 100mm diameter core.

Static triaxial strength was measured on 200mm long, 100mm diameter cored samples. The specimens were instrumented with two longitudinal and two circumferential strain gauges, wrapped in a flexible open-ended neoprene sleeve and placed in a triaxial test cell.

High strain-rate compression testing was carried out in a Split Hopkinson Pressure Bar, at strain rates around 10^3 strain/second, typical of the peak local to the point of impact of the dropped drum, but much larger than the average strain rate. The principle of the test is to pass a stress wave obtained by a controlled explosive charge through a sample sandwiched between two long cylindrical metal bars.

The dynamic Young's Modulus and Poisson's ratio were determined by passing sound waves through a sample and measuring the velocity of compressive (P) and shear (S) waves.

4.2 Results

All of the waste forms were cured until the rate of increase of strength had reduced to a very low level.

TABLE II summarises some of the test results. In each case the average of between 3 and 30 results is given. FIGURE 3 shows the results of the static triaxial compression tests for Magnox sludge. The results for cement grout were very similar, and are not reported in this paper. The results show the deviatoric stress at failure increasing with hydrostatic pressure, a characteristic of cementitious materials. In this instance, however, the increase is not very large. Work on the high strain rate properties of sludge and grout is still continuing and is not reported in this paper.

TABLE II. SUMMARY OF MATERIALS TEST RESULTS

		STATIC				DYNAMIC	
WASTE	DENSITY (Mg/m^3)	UNCONFINED COMPRESSIVE STRENGTH (N/mm^2)	TENSILE STRENGTH (N/mm^2)	YOUNG'S MODULUS (N/mm^2)	POISSON'S RATIO	YOUNG'S MODULUS (N/mm^2)	POISSON'S RATIO
MAGNOX SLUDGE	1.39 ±0.06	3.87 ±0.24	0.67 ±0.05	1.91×10^3 $\pm0.23\times10^3$	0.204 ±0.045	4.47×10^3 $\pm0.24\times10^3$	0.343 ±0.0
MAGNOX SWARF	1.92 ±0.08	17.63 ±12.77	3.20 ±0.23	1.77×10^4 $\pm0.57\times10^4$	0.23 ±0.05	2.43×10^4 $\pm0.57\times10^4$	0.28 ±0.04
ION EXCHANGE RESIN IN DOW	1.06 ±0.01	18.8 ±6.6	6.58 ±0.48	6.93×10^2 $\pm0.63\times10^2$	0.53 * ±0.04	- -	- -
CEMENT GROUT	1.47 ±0.07	3.95 ±0.28	1.03 ±0.05	1.89×10^3 $\pm0.21\times10^3$	0.19 ±0.02	2.36×10^3 $\pm0.11\times10^3$	0.13 ±0.02

* Result unconfirmed

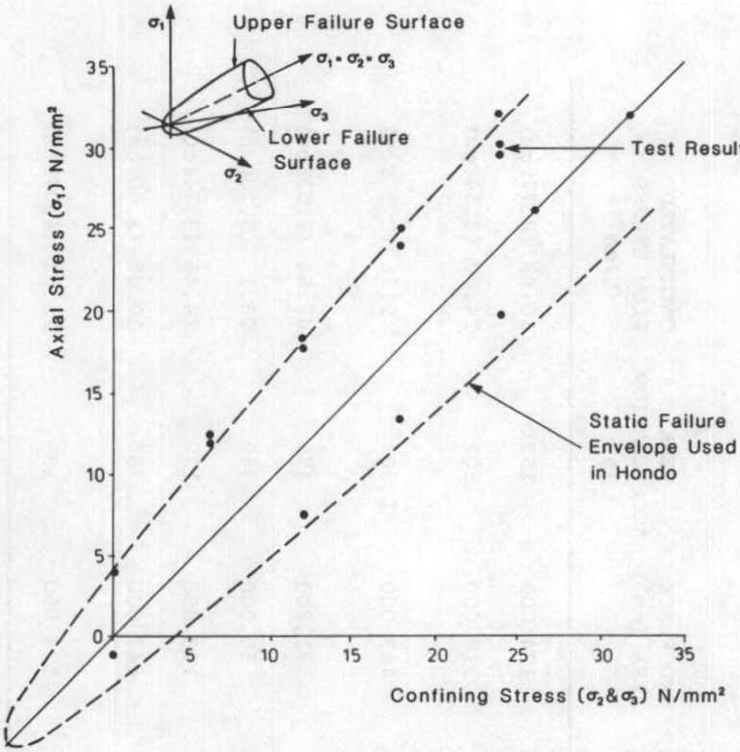

FIG. 3. Magnox sludge triaxial test results and HONDO failure envelope.

5. DRUM DROP TESTS

5.1 Description

The drum drop tests and the corresponding materials tests were carried out at around the same time, so as to make the results as comparable as possible. Each drop test was instrumented with two accelerometers mounted adjacent to each other, opposite the impact point. From these the impact forces were estimated. The deformation of the drum along the line of reaction (known as the knockback), and the maximum area of the drum in contact with the anvil (known as the knockback area) were both measured after each drop test.

5.2 Results

The performance of the drum in all the tests was very satisfactory. In all tests, except test No. 1, the drum skin remained intact and did not allow release of contents. In test No. 1 (9 metres onto bottom edge, with weak cement grout) a

TABLE III. SUMMARY OF DROP TEST RESULTS

TEST No. (CONTENTS)	ATTITUDE & HEIGHT	KNOCKBACK (mm)	KNOCKBACK AREA (mm^2)	PEAK ACCELERATION (g)	CALCULATED FLOW STRESS (N/mm^2)
1 (GROUT)	CORNER (9m)	105	174 000	152	10.93 (2.77Fcu)
2 (GROUT)	AXIS HORIZONTAL (9m)	25	318 000	502	14.00 (3.54Fcu)
3 (GROUT)	AXIS VERTICAL (36m)	78	443 000	1,904	9.36 (2.37Fcu)
4 (DOW)	CORNER (9m)	50	71,300	476	47.64 (2.53Fcu)
5 (SWARF)	CORNER (9m)	46	50,000	369	93.1 (5.28Fcu)
6 (SLUDGE)	CORNER (9m)	92	123 880	179	14.46 (3.74Fcu)
7 (SLUDGE)	AXIS VERTICAL (36m)	70	447 000	780	10.06 (2.60Fcu)
8 (SLUDGE)	CORNER (9m)	87	124 850	189	16.52 (4.27Fcu)

narrow split occurred at a weld and about 10 grams of cement grout were ejected. This test had the largest knockback. The split occurred in a region of high tensile strain caused by the knockback.

TABLE III summarises the results of all 8 tests. These were analysed in a number of ways, starting with simple hand calculations, proceding to computer-assisted lumped-mass calculations and finally non-linear dynamic finite element calculations using the computer code HONDO [2].

The simplest analysis involved equating the energy of deformation of the drum with the kinetic energy of the drum at impact minus the rebound energy. The deformation energy is calculated by assuming that the contact stress (or flow stress) between the anvil and drum is constant. By integrating the impact force (= flow stress x area) with distance along the line of reaction, it is found that:

Deformation energy = flow stress x volume of knockback.

Using this formula, the value of flow stress to be used for each different matrix was calculated, and is shown in TABLE III. It is also expressed as a multiple of the unconfined compressive strength, Fcu. The flow stresses shown in TABLE III are all several times greater than the unconfined compressive strength, and this is due mainly to the triaxial confinement and strain-rate effects.

For preliminary estimates of drum deformations the use of this method, using a value of average flow stress selected by reference to TABLE III, will yield reasonable results. For the bottom edge attitude, however, it was found that the assumption that flow stress was constant throughout the event led to discrepancies which could only be explained by postulating that the flow stress decreases with knockback. Refinement of the simple hand calculations using one-dimensional lumped mass modelling, taking account of the reduction of flow stress with knockback explained to some extent the experimental variation in the results shown in TABLE III. For example, for the bottom edge attitude the deduced average flow stress varied from 2.73Fcu (for grout) to 5.30Fcu (for swarf). The former, 2.73Fcu, occurred when the knockback was greatest and the latter, 5.30Fcu, occurred when the knockback was least. This trend is indicative of decreasing flow stress with knockback and the one-dimensional lumped-mass calculations indicated that this effect is expected.

The last technique used was non-linear dynamic finite-element analysis. A two-dimensional axisymmetric model of the axis vertical attitude was made using the measured properties of

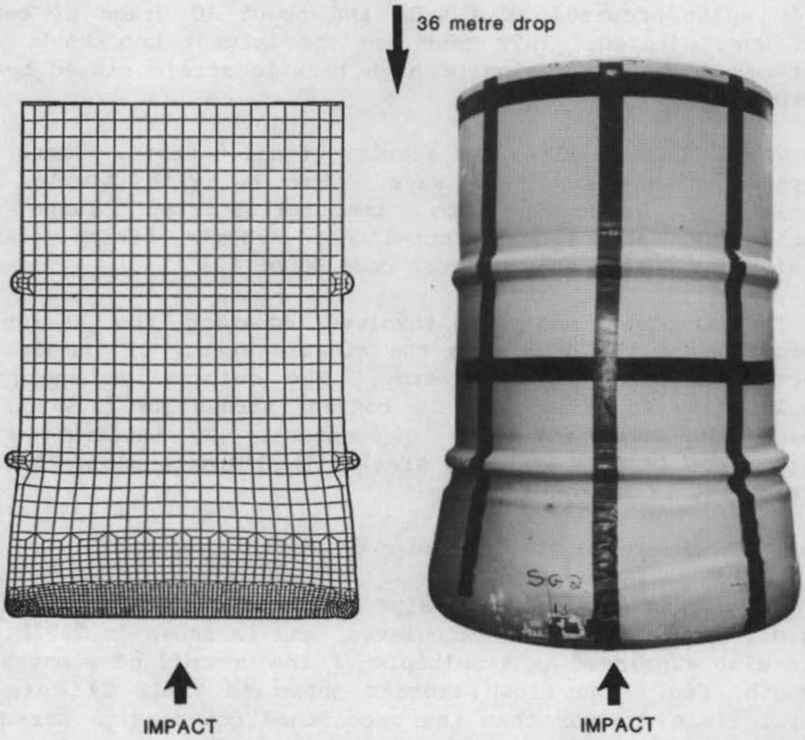

FIG. 4. Comparison of actual and calculated deformations for axis vertical drum drop.

the Magnox sludge and the results compared with the experimental results. The impact velocity, corresponding to 36 metre drop height, was chosen to give a large volume of knockback. The sludge was modelled as an elastic - perfectly plastic material, whose yield strength at any point depended upon the hydrostatic pressure at that point (using HONDO's soil and crushable foam material model). When the program was run making allowance in the sludge properties for strain-rate effects, the calculated knockback was too small. When the program was run with no allowance for strain-rate effects, then the results agreed with experiment. FIGURE 3 shows the failure surface used in the model. It is likely that the strain-rate effects are being offset by other effects not modelled by computer, eg. inelastic behaviour at stress levels less than the failure stress. FIGURE 4 shows the drum from the drop test and the deformed finite element mesh. The agreement is seen to be very good. The analysis shows that the strains in the sludge are confined to the bottom 1/3. The model may now be used to test the sensitivity of the drum to design changes.

6. CONCLUSIONS

The following conclusions may be drawn:

1. With a few exceptions, the conventional testing of all the matrices and the investigation of the triaxial behaviour of the cement paste and the Magnox sludge yielded results that are consistent with expectations.

2. Drums of immobilized ILW can be very robust and capable of large deformations before rupture of the drum skin occurs.

3. Techniques of estimating the deformations of the drums during an impact event using the results of standard laboratory tests on immobilized waste forms have been developed. The techniques include simple hand calculations, simple computer-assisted lumped-mass calculations and finite element techniques.

4. These techniques enable the results of drum drop tests to be better understood and to be extrapolated to conditions not tested, thereby reducing the number of physical tests normally required.

5. Further work should be carried out, but in the meantime the likelihood of a breach may be postulated by an assessment of knockback and deformation of the drum.

ACKNOWLEDGEMENTS

Materials testing was carried out by by Wimpey Laboratories Ltd, Drop testing of drums by the CEGB Structural Test Centre Cheddar. Drum filling with Dow Polymer was done by CEGB Wythenshawe, with Magnox sludge and Magnox swarf by AEE Winfrith, with cement grout by Wimpey Laboratories Ltd. The paper is published by permission of UK Nirex Ltd.

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