FIELD et al.

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LIQUID JET IMPACT AND DAMAGE ASSESSMENT FOR BRITTLE SOLIDS
J.E. Field, D.A. Gorham, J.T. Hagan, M.J. Matthewson
M.V. Swain and S. van der Wagt.

Physics and Chemistry of Solids
Cavendish Laboratory
Madingley Road
Cambridge U.K.

Recent liquid impact work in this laboratory is reviewed. Improved
type designs have allowed jets of small diameter to be obtained reproducibly.
These smaller jets simulate spherical drop impact down to equivalent
drop diameters of ~2mm. A hydraulic strength test apparatus is described
for measuring post impact "residual strengths". Residual strength curves
are given for soda-lime glass and various types of silicon nitride. Strength
measurements on specimens subjected to angled impact show that in some
situations an oblique impact can cause a greater strength loss than normal impact.
The results of jet impact on zinc selenide and zinc sulphide are discussed.
The final section describes experiments on Rayleigh surface wave/defect in-
teractions.

INTRODUCTION

This paper reviews some of our recent
liquid impact work at Cambridge. We have
been using three different techniques for stu-
dies of high velocity liquid/solid impact.
The first involves projecting specimens of up
to 25.4mm diameter against stationary drops.
The second fires liquid jets at a stationary
target. The third uses 2-D liquid configura-
tions (discs, wedges of liquid) which are
impacted. The first type of experiment is
nearest to the practical situation in rain
erosion. The second has distinct advantages
in its ease of operation, low construction
cost and the velocity range which can be
covered. The final approach, using 2-D
configurations, allows processes occurring
inside the impacted liquid to be followed by
high-speed photography, and is also closer
to situations which can be theoretically an-
alysed. The first part of this paper des-
cribes recent developments with the jet meth-
od. The theoretical and experimental work
on 2-D impact is given in a separate paper
at this Conference by Field, Lesser and
Davies (1).

Since the early 1970s we have attempted
to place damage assessment on a sounder
quantitative basis by measuring post impact
"residual strengths". This involves impact-
ing a specimen under known conditions and
then measuring its strength. A hydraulic
apparatus, which stresses disc specimens,
have been developed for this work. Examples
of "residual strength" curves have been given
in earlier papers (2,3,4). Curves for various
types of silicon nitride, and for glass spec-
imens subjected to oblique impact are pre-
sented below. It is shown that under certain
conditions oblique impact can cause a greater
decrease in strength than a normal impact.

Zinc sulphide and zinc selenide are both materials which have useful infra-red
transmitting properties. We have recently
studied the damage caused by jet impact and
a selection of results is given in this paper.

When a liquid impacts a solid at high
velocity, an intense Rayleigh surface wave is
generated which can cause circumferential
cracking as it moves out from the impact area
(5). A systematic study has recently been
made by two of us (Swain and Hagan 6) of the
interaction between Rayleigh surface waves
and artificially induced defects of known di-
mensins. A brief account of this work is in-
cluded.

Many materials can only withstand li-
quid impact if they are covered by a protect-
ive coating. This is an area we are actively
studying. Our theoretical and experimental
work on elastomeric coatings is described in
a separate paper at this Conference by
Matthewson (7).

JET IMPACT

The jet method was first devised by
Brunton (8,9). A projectile is fired into a
stainless steel chamber containing water se-
aled in by a neoprene disc. The projectile
and neoprene drive forward as a piston and ex-
trude the water through an orifice. The ratio
of jet velocity to projectile velocity is typi-
cally 3-5. In references (2,4) we have
described how the 60° nozzle of Fig.1a could
be used to produce jets of different sizes by
varying the diameter of the orifice d. A
detailed study of jet and spherical drop im-
 pact enabled us to work out the "equivalent
drop" size for the jets over a range of velo-
cities (4,10).Fig.2 gives these curves for
0.4,0.8 and 1.6mm diameter orifices. The 0.4
mm orifice jet reproduces 2mm diameter drop
impact for velocities in the range 200-600m/s-1.
Since a rain drop may have an oblate shape
when impacted, and hence a much larger effec-
tive radius in the contact region, impacts by
larger jets are also of interest. Drop sizes
intermediate between the curves can be simu-
lated by choosing an orifice size by interpo-
lation. Very much larger jet diameters and
velocities can also be produced but these are
of more practical interest in mining applica-
A disadvantage of using the chamber of Fig. 1a for a wide range of jet sizes is that it is not optimized for a particular jet size. Recently we have studied various types of nozzle design in an attempt to improve the reproducibility of our 0.4 and 0.8mm jets. Figs. 1b and c show the nozzles which have resulted from this research. In brief, with smaller diameter jets, it helps to reduce the 60° of the Fig. 1a nozzle to \( \approx 45° \). Further, if smoothing of the inside angles is practicable this also helps. This smoothing process is not easily performed with the 0.4mm nozzle and so the design of Fig. 1b is used. However, with the 0.8mm nozzle it is possible and the "curved" nozzle of Fig. 1c has been adopted. Both new nozzles are loaded to the full position (\( P \)), with the liquid/air interface convex outwards.

The reproducibility of the jets was studied by taking high-speed photographs and by measuring damage marks on PMMA (polymethylmethacrylate). The results showed that if the chambers were loaded carefully (i.e. no gas bubbles or solid particles in the liquid) good coherent jets were produced each time. Compared with the nozzle of Fig. 1a the scatter in damage dimensions was reduced by about 60%. A disadvantage of using the chamber of Fig. 1a for a wide range of jet sizes is that it is not optimized for a particular jet size. Recently we have studied various types of nozzle design in an attempt to improve the reproducibility of our 0.4 and 0.8mm jets. Figs. 1b and c show the nozzles which have resulted from this research. In brief, with smaller diameter jets, it helps to reduce the 60° of the Fig. 1a nozzle to \( \approx 45° \). Further, if smoothing of the inside angles is practicable this also helps. This smoothing process is not easily performed with the 0.4mm nozzle and so the design of Fig. 1b is used. However, with the 0.8mm nozzle it is possible and the "curved" nozzle of Fig. 1c has been adopted. Both new nozzles are loaded to the full position (\( P \)), with the liquid/air interface convex outwards.

Fig. 3 shows a single shot picture of a jet from a 0.8mm nozzle. The umbrella of spray comes mainly from the water in the parallel section of the orifice. It is made up of droplets of micron size which do not contribute to the damage. The jet front velocity increases over a distance of about 10mm. This is clearly shown in Figs. 4 and 5 where jet velocity versus distance travelled is plotted. This behaviour is reasonable since it is only the liquid in the main part of the chamber which is accelerated through the nozzle section and it takes a finite distance.

Fig. 2. Equivalent drop size as a function of impact velocity for jets of different sizes.

Fig. 3. Single shot photography of a jet from a 0.8mm nozzle.

cations. (The problems eventually encountered in producing very high velocity jets have been discussed elsewhere, 11.) The great advantage of knowing the equivalent drop size is that it allows the jet method to be used for obtaining, at least some of, the impact data; rather than the much more experimentally complex moving specimen/stationary spheri-
Fig. 4. Jet velocity versus distance at different firing pressures for a 0.4 mm nozzle. Note a plateau value is reached for a stand-off distance of ~10 mm.

Fig. 5. As for Fig. 4 but for a 0.8 mm nozzle.

Fig. 6. High-speed photographs taken with an interframe interval of 1 μs for jets from (a) 1.6 mm, (b) 0.8 mm and (c) 0.4 mm nozzles.
HYDRAULIC STRENGTH TESTER

The apparatus, first described by Field et al (2) and then in more detail by Gorham and Rickerby (3) is shown schematically in Fig. 7. The 25mm radius disc specimen is supported by a ring near its edge. A neoprene diaphragm transmits a uniform hydrostatic pressure across the entire rear surface of the disc. The pressure in the hydraulic system is increased until the specimen bursts and from the bursting pressure and position of the fracture origin and its orientation, the fracture stress \( \sigma_f \) may be calculated.

![Fig. 7. Schematic diagram of the hydraulic strength testing apparatus.](image)

This technique for measuring fracture strengths of materials has several advantages over other methods.

i) Edge failures, common in tensile, 3- or 4-point bend tests, are largely eliminated.

ii) Compared with the ring-on-ring test there is little stress concentration due to the applied load, there is less effect due to warped specimens, and the area of the sample under test is larger.

iii) The method is rapid in operation, allowing examination of the large number of specimens which are required for a statistical analysis of the data. Materials such as glass have fracture properties which are essentially stochastic in nature.

iv) The principal stresses in the specimen surface are sensibly equal over a large area at the centre of the disc. Thus the probability of failure at a certain flaw is not a sensitive function of its orientation to the applied stress field.

v) The apparatus may readily be miniaturised. This is useful for examining properties of costly materials.

vi) Specimens can be impacted when under stress in the hydraulic apparatus, allowing the effect of pre-stress to be studied.

It has been found that for thicker specimens \((t > 6mm)\) the fraction of specimens which fail at the edge can be large (\( >10\% \)) resulting in a loss in accuracy of the results. Edge failures are caused by an interaction of the large tensile hoop stress here with stress inhomogeneities at the support. If the support ring radius is decreased the hoop stress is significantly reduced and it has been shown that edge failures are less frequent (\(<5\% \)) and may be ignored. However, the stress distribution in the disc found by Timoshenko (12) and used by Gorham and Rickerby is no longer valid as it assumes the disc is supported at its edge. A more applicable stress distribution has been found by one of us (13). The radial and circumferential surface stresses are given by

\[
\sigma_r = \frac{3Pr}{8t^2} \left( \frac{\rho^2}{(3+\nu)-4(1+\nu)\ln} + 2(1-\nu) \right) - (3+\nu) \left( \frac{\rho^2}{2} + \sigma_0 \right)
\]

\[
\sigma_\theta = \frac{3Pr}{8t^2} \left( \frac{\rho^2}{(3+\nu)-4(1+\nu)\ln} + 2(1-\nu) \right) - (1+3\nu) \left( \frac{\rho^2}{2} + \sigma_0 \right)
\]

where \( P \) is the applied pressure, \( t \) the plate thickness, \( r \) the disc radius, \( r_1 \) the support ring radius, \( \nu \) the Poisson ratio, \( \rho = r_1/r_0 \), and \( \sigma = \sigma_0/\rho \). The term \( \sigma_0 \) is a correction for finite plate thickness given by Timoshenko as

\[
\sigma_0 = \frac{(3+\nu)\rho}{4(1-\nu)\rho}
\]

OBLIQUE IMPACT ON GLASS

The residual strength of soda-lime silicate glass discs has been found as a function of the impact angle for impacts by jets from a 1.6mm nozzle. At the 10mm stand-off distance these jets have a head diameter of \( 2\text{mm} \) at an impact velocity of \( 200 \text{m s}^{-1} \) and \( 2\text{mm} \) at \( 620 \text{m s}^{-1} \) (2). However, before describing the results it is useful to examine the results for normal impact by these jets (4).

Fig 8 shows the variation of fracture stress, \( \sigma_f \), with the impact velocity \( V \). Above a velocity of \( 200 \text{m s}^{-1} \) the residual strength falls from its unimpacted value of \( 75 \text{MPa} \) and reaches a value of \( 0.8 \text{MPa} \) at \( 300 \text{m s}^{-1} \). Above \( 300 \text{m s}^{-1} \) the strength remains approximately constant. The form of the curve has been interpreted by Field et al (4) in terms of the processes involved in the impact. The liquid jet at first contact with the specimen behaves compressibly and the well known "water-hammer" pressure is generated. This is approximately given by \( \rho CV \) where \( \rho \) is the density of the water and \( C \) the shock wave velocity in water. This high pressure is maintained for the time it takes a relief wave to travel from the outer boundary to the centre of the jet. The duration of the \( \rho CV \) pressure is therefore given by \( \tau/C \) where \( \tau \) is the jet radius. Thus the pressure history is characterised by a short duration intense pulse of pressure (\( \approx 1 \text{GPa} \) for \( \approx 1 \text{s} \))
followed by a much lower sustained pressure. An intense stress wave is propagated into the specimen with an amplitude and duration given approximately by $\rho CV$ and $\tau$. Thus if the stress wave causes growth of an existing flaw in the surface it can only grow for the duration of the pulse and its length will depend on $\tau$ and not on the impact velocity, V. Therefore for $V \leq 300 \text{ m s}^{-1}$ the fracture strength is approximately constant. The slight fall with velocity is due to a small increase in the jet diameter with velocity ($D$), and also to additional growth of flaws caused by interactions with stress waves reflected from the specimen boundaries. In the transition region ($200-300 \text{ m s}^{-1}$) the impact may or may not cause a flaw to extend to the point where it significantly reduces the strength of the specimen and the data points represent the mean of a bimodal distribution of fracture stresses.

Returning to oblique impact, the residual strength of glass has been found as a function of impact angle, $\alpha$, for four representative impact velocities, $\alpha$ is defined as the angle between the jet and a normal to the target surface. Fig. 9 shows the results. The stresses were calculated using $\eta = 23 \text{ mm}$, $r_J = 25 \text{ mm}$, $t = 6 \text{ mm}$ and $\varphi = 0.25$. Each data point represents the average for ten specimens.

For the two lower impact velocities ($250$ and $300 \text{ m s}^{-1}$) the residual strength is seen to rise monotonically to the unimpacted fracture strength as the obliquity increases. However, for the higher velocities the strength passes through a minimum at a non-zero impact angle before rising to the unimpacted strength. Clearly the damage does not depend in a simple way on the component of impact velocity perpendicular to the target surface, namely $V_{\text{com}}$. Fig. 10 shows the sketched lines of Fig. 9 for impact velocities of $250$ and $620 \text{ m s}^{-1}$ (solid lines). Also shown are dashed lines which would show the behaviour of residual strength with impact angle if the damage were the same as that caused by normal impact with a velocity equal to the normal component of velocity for oblique impact. It can be seen that at $250 \text{ m s}^{-1}$ the residual strength rises far more rapidly towards the undamaged strength than the assumption $V_{\text{com}}$ would predict. This behaviour is also observed for $620 \text{ m s}^{-1}$ impacts once the anomalous minimum of strength is passed. This suggests that the damage is better described by a function such as $V_{\text{com}}^n$. The exponent $n$ has been found to be variable but is in excess of 5.

The anomalous low residual strength of samples impacted at higher velocities with small non-zero impingement angles is caused by long radial cracks formed on the impact surface. Fig. 11 shows typical specimens which have been impacted by $620 \text{ m s}^{-1}$ jets for various impact angles. The impact direction is from top to bottom. Radial cracks are clearly visible for impact angles of between $5^\circ$ and $25^\circ$. At $25^\circ$ the radial cracks extend across the entire specimen leaving it with effectively zero residual strength. Radial cracks do not form under normal impact at this velocity. At higher velocities, radial cracks do form under normal impact and are a result of plate bending. They nucleate and grow across the rear surface of the specimen. The radial cracks formed by oblique impact are quite different in nature as they nucleate and grow across the front surface.
The circumferential cracks which are typical of impacts on brittle materials show another interesting feature of oblique impact. The circumferential cracks are produced during the passage of an intense Rayleigh stress wave associated with the impact and are analogous to the Hertzian cone cracks formed when a sphere is loaded on a flat. For oblique impact, these cracks are concentrated in the "downstream" direction and this means that the shock wave is very much more intense here. Also the edge of the specimen shows severe chipping in this direction. The main compressive wave in the bulk of the material reflects in the corner in tension and is focussed leading to failure and material removal. The total area containing circumferential cracks decreases with increasing α, and hence one would expect, in the absence of radial cracks, that damage would be a maximum for normal impact.

The origin of the radial cracks is not entirely clear. However, they appear to extend from an abnormally large circumferential crack at the "upstream" edge of the impact zone. Hamilton and Goodman (14) have analysed the statically analogous case of Hertzian loading with a superimposed tangential stress; the situation of oblique indentation. They found an enhanced tensile stress at the upstream edge of the contact area. The crack found in the present dynamic situation corresponds to a similar stress distribution. The radial cracks clearly do not form during the initial stages of the impact as they are too long to have grown on a microsecond time scale. Their length is attributed to interactions with reflections of the stress waves from the specimen boundaries. Specimens larger in either lateral dimensions or thickness do not exhibit radial cracking in the velocity range considered, and therefore the cracks are a result of specimen geometry.

To summarise, 25mm diameter, 6mm thick glass disc specimens suffer maximum strength loss for off-normal impact at sufficiently high impact velocities. This effect is due to the formation of radial cracks in oblique impact which do not appear for normal impact at the same velocity. The radial cracks form as a result of multiple reflections of stress waves at the specimen boundary and lower surface and may be inhibited by suitable choice of specimen geometry. However, in some practical situations it is impossible to avoid thin specimens and stress wave effects then become important.

**RESIDUAL STRENGTH OF SILICON NITRIDE**

The residual strength has been found as a function of impact velocity for various silicon nitrides. Three materials have been examined, a hot pressed silicon nitride (hereafter denoted HPSN, supplied by F.M.I.) and two reaction bonded silicon nitrides (RBSN1; AMRC) and (RBSN2; Georgia Institute of Technology). For completeness the results of Field et al (4) for another reaction bonded material (RBSN3; AMTE) are also presented.

Fig. 12 presents the residual strength curves for these materials. The results are for impacts by jets from a 0.8mm nozzle (~1mm jet head diameter at the specimen at 350m s⁻¹ and ~1.5mm at 620m s⁻¹, reference 2). The HPSN and RBSN2 results were obtained for impacts by 3mm diameter jets from a 1.6mm nozzle but scaled using the analysis described by Field et al (4) and Rickerby (10). The larger jets were found to be unsuitable as the relatively thin specimens (~3mm) were found to
Fig. 12. Residual strength curves for various silicon nitrides. See text for details. Impacts by jets from a 0.8mm nozzle.

suffer excessive damage at quite modest impact velocities and the threshold velocity could not be found very accurately.

Clearly the HPSN material is the most suitable of those considered for rain erosion resistance as it has a very high undamaged strength, a high damage threshold velocity and a small fall in strength above this velocity.

ZINC SELENIDE; ZINC SULPHIDE

Fig. 13. Liquid jet impact on zinc selenide with a 600m s⁻¹ jet from a 0.4mm nozzle. The equivalent drop size is 2.6mm. (a) upper picture single impact (b) lower picture, a second impact to the right of that shown in (a). The feature labelled A is the same in both.

Fig. 14. Enlarged view of damage for impacts on zinc selenide (a), at left; 600m s⁻¹. The feature labelled A is the same as in Fig. 13 (b) 250m s⁻¹.

Fig. 15. Liquid jet impact on zinc sulphide. Identical experiments to those illustrated in Fig. 13 so direct comparison is possible.

Fig. 16. Liquid jet impact on zinc sulphide. Identical experiments to those illustrated in Fig. 14. Feature labelled B is the same as in Fig. 15.
At present there is considerable interest in these materials due to their good infra-red transmitting properties. Figs. 13-17 show the results of liquid jet impact with them. In all cases jets from a 0.4mm nozzle were used. Fig. 13a is for a single impact on zinc selenide at 600m s⁻¹. This we would predict to be equivalent to impact at this velocity with a drop of ~2.4mm diameter. The figure shows that there is an undamaged central region surrounded by many short circumferential cracks. There are many similarities with impacts on other brittle materials (5,8). Fig. 13b illustrates the effect of a second impact near the first; the second impact is at the right. The original damage is not greatly affected but that associated with the second impact is significantly more intense, showing that the first impact had weakened the material to radial distances of about 2mm.

An enlarged view of the cracked region is given in Fig. 14a, while Fig. 14b shows a similar area but for an impact velocity of 250m s⁻¹. The feature labelled A in the figure identifies the enlarged region. The flow of liquid over the cracks has eroded material from them. As earlier work has shown there is a surface step across each crack which acts as a site for erosion (8,15).

For comparison Figs. 15 and 16 give results for zinc sulphide. Again the velocities involve are 600 and 250m s⁻¹. Compared with the previous results it appears that zinc sulphide is more erosion resistant than the selenide. The amount of cracking is less and the second impact site does not show significantly more damage than the first. The fracture labelled B is the same in each photograph.

Finally, Fig. 17 illustrates the much more severe damage which results at an impact velocity of 900m s⁻¹ on zinc selenide. At this velocity there is subsurface damage in the central region and "cone" and radial cracks have formed.

**DEFECT/RAYLEIGH WAVE INTERACTION**

Many aspects of low velocity impact, erosion and wear phenomena can be simulated and evaluated by quasi-static indentation experiments. This approach has been followed by several research groups. However, it is not possible to extrapolate quasi-static behaviour to high velocity impact situations where high strain rate properties of materials and/or stress wave interactions are important. In this section of the paper we describe experiments in which the interaction between Rayleigh surface waves and surface flaws has been studied. A more detailed account of this work is given in (6).

Artificially induced flaws were introduced into blocks of glass (250x250x25mm) by loading a Vickers indenter against the surface. This method (see references 16,17) produces two well-defined orthogonal semi-circular cracks in planes at right angles to the indented specimen surface. The advantage of using artificial flaws of known dimensions is that it avoids the uncertainties with inherent surface flaws of uncharacterised size, distribution and orientation.

The cracks were introduced at chosen positions and orientated in such a way that their lengths were normal and parallel to the direction of propagation of the Rayleigh wave. The Rayleigh waves were generated by the impact of jets from a 1.6mm nozzle impact velocities of 300 and 550 m s⁻¹. Fig. 18 shows schematically the geometry of the situation. If the distance R is

![Figure 17](image_url) Liquid jet impact at a velocity of 900m s⁻¹ on zinc selenide. No longer an undamaged central region. Cone and radial cracks have formed.

![Figure 18](image_url) Geometry of situation for stress wave/crack interaction experiments.
large the crack at right angles to the wave front is subjected to essentially mode I loading. The experiments were designed to study crack growth and branching as a function of R, the effect of different initial flaw sizes and the magnitude and duration of the Rayleigh wave.

Fig. 19 illustrates the extent of crack growth for three values of R. In each case the small plastic Vickers indents with the orthogonal cracks can be seen. Only the crack normal to the stress front is extended; the arrow marks the direction of travel of the wave. Consequently the trace of the other crack gives a good measure of the initial surface crack length (~100 μm). Fig. 19a is for the crack nearest to the impact site. After a short distance of growth crack branching, or feathering, has taken place. Most of these branches start together. The type of crack illustrated in this figure is very similar to a circumferential crack developed from a natural defect by liquid impact (see Fig. 4 of reference 5). As R increases the number of branches decreases (Fig. 19b) and eventually a stage is reached when branching does not take place (Fig. 19c).

Fig. 19. Surface flaws after interaction with wave produced by a jet of head diameter ~3 mm impacting at 550 m s⁻¹. The markers have lengths of 100 μm.

The total amount of crack growth, including all the branches, as a function of R for impacts from a 1.6 mm nozzle at 300 m s⁻¹ (~2.4 mm jet head diameter) and 550 m s⁻¹ (~3 mm jet head diameter) is shown in Fig. 20.

Fig. 20. Total extent of crack growth for jets from a 1.6 mm orifice impacting at 550 and 300 m s⁻¹. Jet head diameters are ~3 and 2.4 mm respectively.

Attempts to measure the Rayleigh surface wave pulses have been made using 100 μs PZT crystals (6). An alternative approach for estimating pulse durations is to work back from the measured crack dimensions and a knowledge of crack behaviour in glasses. If, for example, it is assumed that the crack extends in both directions at an average value of half its maximum velocity up to the points of branching and at its maximum velocity thereafter then times for the pulse duration can be estimated. Justification for this kind of crack velocity behaviour have been found in separate fracture studies (18). For soda-lime glass the value for the maximum crack velocity is ~1500 m s⁻¹.

Using this approach the cracks at 4 mm and 12 mm, illustrated in Fig. 19, predict that the pulse was intense enough to cause crack growth for 0.52 and 0.36 μs respectively. Assuming a R⁻¹ fall off in intensity for the Rayleigh wave and that its shape is approximately sinusoidal this suggests that the pulse at the edge of the contact region (Rw 1.5 mm) should be about 1 μs. This is the value predicted for a jet of 3 mm diameter.

DISCUSSION

This paper has described a variety of experiments from a general study of liquid impact and the damage it causes. The jet method has many advantages and these have been discussed in earlier papers. The research on jet production discussed here was concerned with improving jets from 0.4 and 0.8 mm orifices. These jets are particularly useful since they simulate drop impact in the size range 2 to 4 mm for a wide range of velocities. The photographic records (Figs. 8 and 9) show
Table 1

<table>
<thead>
<tr>
<th>Material</th>
<th>Initial Strength MPa</th>
<th>50% Velocity m s⁻¹</th>
<th>Post Impact Strength MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soda-lime glass</td>
<td>75</td>
<td>350</td>
<td>35</td>
</tr>
<tr>
<td>Calcium Aluminate glass</td>
<td>125</td>
<td>420</td>
<td>35</td>
</tr>
<tr>
<td>HPSN</td>
<td>265</td>
<td>600</td>
<td>200</td>
</tr>
<tr>
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<td>145</td>
<td>300</td>
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<td>65</td>
</tr>
<tr>
<td>RB5N3</td>
<td>180</td>
<td>400</td>
<td>75</td>
</tr>
</tbody>
</table>

Residual strength results for a variety of materials for impact by jets from the 0.8mm nozzle. * denotes results converted from 1.6mm nozzle data.

that the jets have smooth, slightly curved, front surfaces which make them ideal for simulating drop impact.

The hydraulic strength test has proved to be an extremely useful technique for quantifying the amount of damage introduced in materials by liquid impact. It provides an inexpensive and rapid method for ranking materials for their rain erosion resistance. Table 1 summarises the results for glasses and silicon nitrides which we have studied.

An interesting off-normal impact anomaly has been found for glass and has been shown to be a result of stress wave interactions with the specimen boundaries and is controlled by the specimen geometry. The nature of the phenomenon implies that it is likely to occur in any brittle material of suitable dimensions; for example, in thin plates or near a boundary. In the absence of radial cracks the damage fails very rapidly with increasing obliquity.

For completeness, it is worth noting that other stress wave interaction mechanisms can also be important. For example, at high velocities, liquid impact on thin plates can cause "bands" of fracture around the impact site. The "bands" are due to the reinforcement of the Rayleigh wave on the front surface by reflected waves from the rear surface (5).

Jet impacts on zinc selenide and zinc sulphide have been illustrated. Our prediction is that the damage illustrated in Fig. 13-16 would be similar to that produced by impact with 2.4mm diameter drops.

The final section of the paper describes a method by which flaws of known dimensions can be added to brittle solids. In the research described this was used to study the interaction between Rayleigh surface waves produced by impact and the defect. This kind of experiment gives useful information on both the stress pulses produced by impact and crack growth in the liquid impact situation.

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