EROSIVE EFFECTS OF HYDROGEN JET FIRES ON TUNNEL STRUCTURAL MATERIALS

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ABSTRACT

This paper presents work undertaken as part of the Hytunnel-CS project, a consortium investigating safety considerations for fuel cell hydrogen (FCH) vehicles in tunnels and similar confined spaces. This test programme investigated erosive effects of an ignited high pressure hydrogen jet impinging onto tunnel structural materials, specifically concrete as used for tunnel linings and asphalt road surfacing for the road itself. The chosen test conditions mimicked a high-pressure release (700 bar) from an FCH car as a result of activation of the thermal pressure relief device (TPRD) on the fuel tank. These devices typically have a release opening of 2 mm and thus, a nozzle diameter of approximately 2 mm was used. The resultant releases were ignited using a propane pilot light and test samples were placed in the jet path at varying standoff distances from the release nozzle.

An initial characterization test of a free unimpeded ignited jet demonstrated a rapid and intense temperature increase, up to 1650 °C, lasting in the order of 3 - 5 minutes for that fuel inventory (4 kg hydrogen). Five tests were carried out where the ignited jet was impinged onto five structural samples. It was found that erosion occurred in the concrete samples where no fire mitigation, namely addition of polypropylene fibres, was applied. The road-surface sample was found to become molten but did not progress to combustion.

Post-test material analysis, including compressive strength and thermal conductivity measurements, was carried out on some of the concrete samples to investigate whether structural deformities had occurred within the sample microstructure. The results suggested that the erosive damage caused by the hydrogen jet was mostly superficial and as such, did not present an increased fire risk to the structural integrity to that of conventional hydrocarbon fires, i.e. those that would result from petrol or diesel fuel tank releases. In terms of fire resistance standards, it is suggested that current fire mitigation strategies and structural testing standards would be adequate for hydrogen vehicles on the road network.

1.0 INTRODUCTION

It is envisaged that hydrogen as a fuel will play an essential role alongside battery technologies in the attempts to decarbonise transport; over 56,000 hydrogen fuel cell (FCH) passenger vehicles were sold worldwide by the end of 2022, according to Information Trends reporting [1]. The increasing volume of FCH vehicles, with their alternative fuel, on the road network does, however, raise concerns in terms of safety of users and continued appropriateness of the existing road standards.

From a safety perspective, hydrogen has the advantage that it is very buoyant and so would rise and rapidly disperse from an area, mixing with air such that the resultant hydrogen cloud would have a concentration below its flammable limit of 4 vol%. Hydrogen has a density of 0.0838 kg/m^3 (NTP), far below that of air, which has a density of 1.205 kg/m^3 under the same conditions [2]. However, there are parts of the road network where the vehicle is not open to the environment and thus gas releases may not be able to disperse as quickly due to the confinement of the location, e.g. tunnels, underground car parks, garages etc.

In addition, hydrogen has a considerably wider flammability range than typical vehicle fuels, e.g. 1-7.6 vol% for petrol vs. 4-75 vol% for hydrogen, as well as a low ignition energy, i.e. 0.017 mJ[3] and so could be easily ignited if an ignition source interacted with a venting hydrogen tank. Previous studies have shown that hydrogen burning in adiabatic conditions can be expected to reach temperatures of 2210 °C[4], a substantial difference to the 1370 °C that is suggested for a severe hydrocarbon fire, such as from a petrol tanker, in a tunnel[5].

The potential for fire and degradation of the structure is of course considered in tunnel design; additional structural material layers offering fire protection include application of a secondary cementitious layer to the tunnel surface, or incorporation of specific fibres, e.g. polypropylene (PP) fibre, into the concrete mix to reduce internal stresses when subjected to fire[6].

In order to ensure that the chosen fire protection measures are appropriate for their intended structure, a series of standard fire scenarios have been established for testing, modelling, and design purposes. The scenarios, based on real fire experiments, are typically represented as a time-temperature curve, where the materials of interest are exposed to an increasing temperature profile over a time period that is representative of the potential fire progression that may occur in that scenario. These time-temperature fire curves have been incorporated into standards, such as ISO 834[7], and have facilitated classification of building elements based on their durability in specified fire conditions. The fire scenarios are typically of long duration, e.g. the RWS fire curve[5] (representing a severe hydrocarbon fire, such as from a petrol tanker, in a tunnel) accounts for tunnels reaching 1200 °C in 10 minutes, 1370 °C in 1 hour and cooling to a steady state of 1200 °C over 2 hours. The structural elements will get significantly heated over this time duration, causing degradation of the mechanical properties and possible structural failure.

For example, when concrete is subjected to high temperatures, i.e. >300 °C, the aggregates and steel reinforcements (if present) begin to expand. At the same time shrinkage also occurs due to “burning off” of the water content, forming steam. These thermal effects, depending on the composition of the concrete, can result in formation of cracks or spalling. In general, the design of precast concrete tunnel segments incorporates a 50 – 100 mm sacrificial layer on the inside of the tunnel, so once explosive spalling is mitigated fire cannot affect the structural concrete behind. Previous research has noted that the severity of spalling appears to be greater when the sample is exposed to a slower heating rate rather than a faster heating rate [8, 9].

A fire scenario for a vehicle tank rupture, where the fuel is hydrogen, would be expected to provide a short, i.e. of the order of minutes, but very intense, momentum driven flame, which would most likely impinge on the tunnel structure for the majority of the release time. This mechanism of rapid local heating, i.e. in contrast to the longer more gradual heating of a typical fire test, is known to also negatively affect concrete and steel materials. However, there is not much research regarding the effect of heating by a hydrogen jet specifically. This experimental programme aimed to investigate the erosive effects, if any, of hydrogen jet fires on structural materials, and the efficacy of addition of PP fibres, a common fire protection measure, against hydrogen fires. The overall aim was to begin to define elements that could form part of a standard materials test for protective materials from a representative burning hydrogen jet and to provide recommendations for relevant Regulations, Codes, and Standards (RCS).

2.0 EXPERIMENTAL SETUP

2.1 High pressure hydrogen release (HPHR) test facility

A diagram of the experimental setup is shown in Figure 1. The test facility comprised a gas booster compressor, which was used to charge two 49 L steel storage vessels from a hydrogen delivery pack pressure of <175 bar up to 700 bar hydrogen. These components were connected via a series of branched pipework, which allowed for releases to be initiated from one or both vessels. The test facility was controlled remotely via a SCADA (Supervisory Control and Data Acquisition) control system, where pressure and temperature readings from sensors on the facility provided feedback to the control system as to the status of the facility. The vessels and pipework were protected from potential fire impingement by directing the final release pipework through a protective pendine block blast wall. The release pipework was orientated horizontally and at a height of 1.125 m from the ground. This orientation is not typical of FCH vehicles i.e. vent lines in FCH cars are typically oriented downwards towards the road (or vertically upwards in the case of buses or trains). However, as the jet is momentum driven and the samples were placed relatively close i.e., 1 m approximately, it was concluded that buoyancy effects would be minimal in this region of the jet and thus results would be comparable with tests where the vent line is oriented vertically. A downward orientation would more likely result in damage to the adjacent sensors and valves (as occurred with the road surfacing sample where the jet was angled downwards) and induce large reactive forces on angle pipework. The nozzle used for the releases was a Fitok AMH series adapter fitting, which gave a diameter of 2.1 mm as confirmed with microscopic measurement. For one test, a 0.57 mm nozzle diameter (HiP NPT 15000 psi series fitting) was used instead, so as to achieve a longer jet blowdown time, thus investigating the effect of prolonged fire impingement on the concrete test sample. The jet was ignited using a propane pilot light, which was positioned approximately 200 mm horizontally downstream from the nozzle.

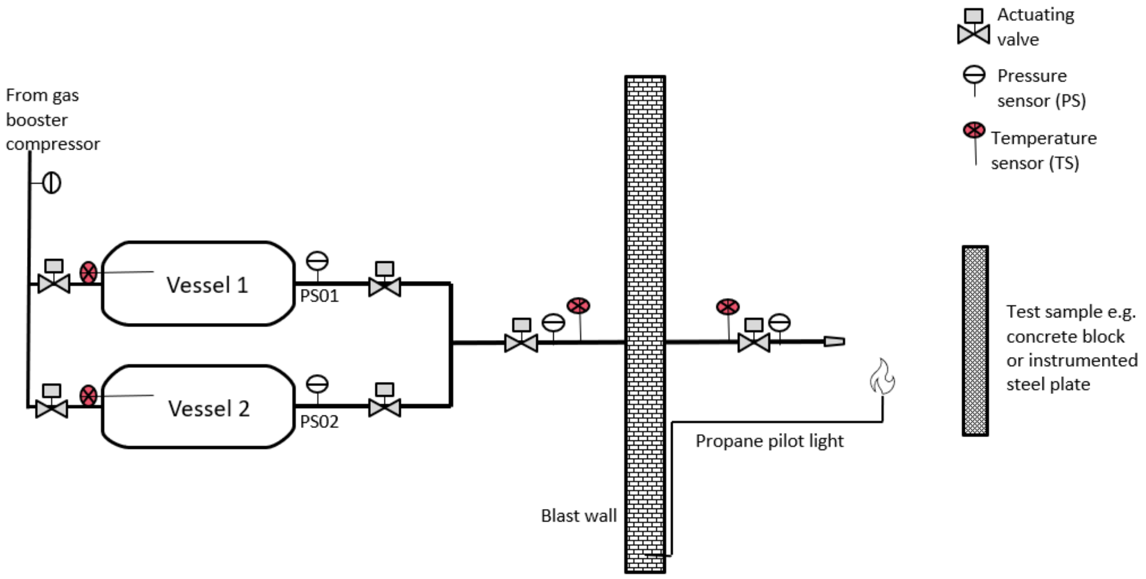


Figure 1: Experimental setup of release. Hydrogen is pressurised to 700 bar from gas booster compressor and stored in two storage vessels (49 L volume each). Releases are initiated by activation of pneumatically controlled valves, with gas blowdown being directed through blast wall, where it is ignited using a propane pilot light. Gas pressure and temperature are monitored at stages along the pipework. Test sample is placed in front of release point

2.2 Materials samples

The chosen samples aimed to replicate the materials that are used for the final layers of the tunnel structure and the road surface, as these are likely to suffer the most serious effects from hydrogen jet impingement. It was decided to focus on high strength concrete specifically, i.e. compressive strength greater than 40 MPa, as high strength concrete is typically used in large structures, such as tunnels. A set of smaller (than typical precast tunnel segments) concrete samples were cast as shown in Figure 2 (a), having dimensions 800x800x400 mm, a compressive strength of 55 MPa and water/cement ratio of 0.45. Within the limitations of what the supplier could use/produce, the specified concrete composition aimed to incorporate some properties that have been known to influence whether explosive spalling occurs, namely concrete strength and moisture content. Concrete is known to be subject to explosive spalling where the design strength approaches 60 MPa and above, and/or contains greater than 3% moisture content [10, 11]. Two of the test samples were cast with polypropylene (PP) fibres to provide comparative samples for efficacy of PP fibres against spalling. One test sample that is typical of road covering material was made. It was asphalt based with hot cure bitumen as the binder and poured into a mould, giving a sample with dimensions 800x800x45 mm, as shown in Figure 2 (b).

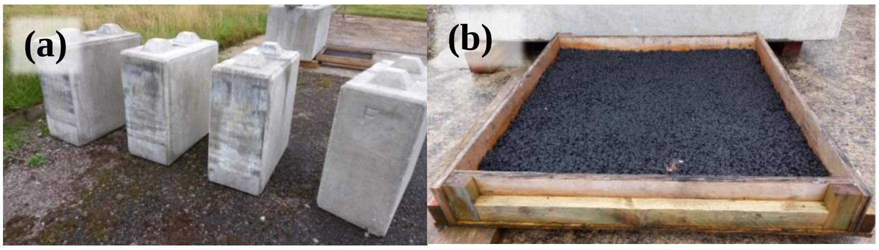


Figure 2: (a) Concrete test samples used. Dimensions 800x800x400 mm, high strength concrete (55 MPa). Polypropylene (PP) fibres were added to two of the samples to investigate their fire resistance efficacy (b) road surfacing material, dimensions 800x800x45 mm

In summary, the materials that were fabricated were, high strength concrete (2 samples), high strength concrete with PP fibres (2 samples), asphalt-based road surfacing (1 sample).

2.3 Test conditions

Unimpeded jet release – sensors and equipment

One unimpeded jet release, i.e. with no samples placed in the jet path, was carried out to gain some insight into the flame length and temperature when unimpeded. Five type ‘R’ sheathed Pt/Rh 3 mm diameter thermocouples were positioned axially along the centreline of the jet, spaced up to a range of just over 3 m, as shown in Figure 3. Thermocouple readings were logged at a sampling rate of 1 Hz using a dedicated National Instruments (NI) thermocouple input module (NI-9213). One vessel (49 L volume) was used for the release, giving a blowdown time of just over 100 seconds. The blowdown pressure data from pressure sensor PS02 (Wika IS-3 standard, 0-1000 bar range) was logged.

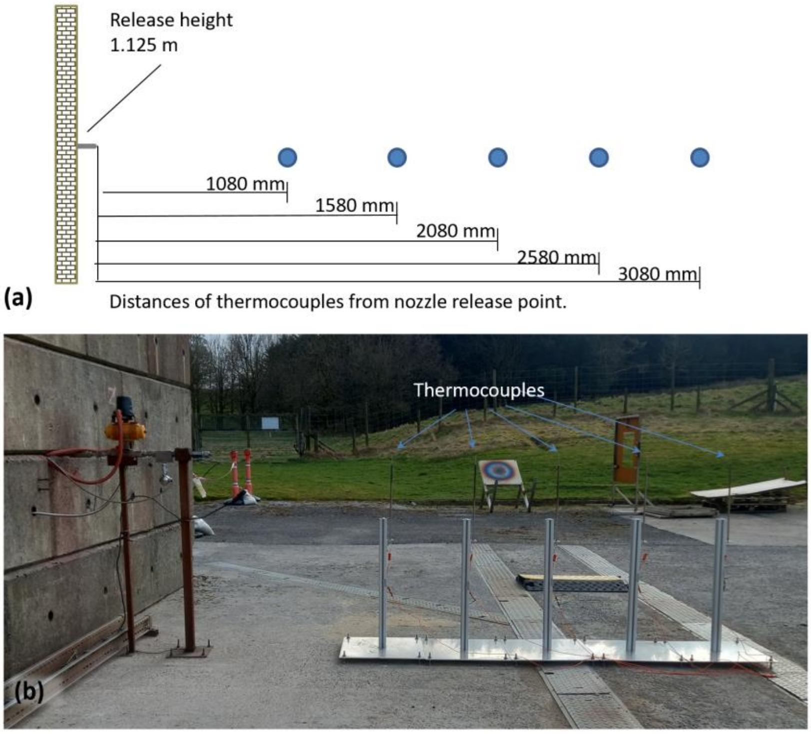


Figure 3: Unimpeded jet release; 2.1 mm nozzle, 700 bar, 49 L volume. Graphic (a) and Image (b) show the spacing of the thermocouples along the axial length

Concrete samples –visual assessment and material analysis

Four jet releases onto concrete were carried out. Each concrete sample was impinged upon by the full available volume, i.e. both vessels with combined volume of 98 L and at a pressure of 700 bar. No additional load or external compression was applied to the samples during testing. The stand-off distance was varied depending on what aspects were being tested, e.g. how standoff distance affected the likelihood of occurrence of spalling. The test using the smaller nozzle diameter, namely 0.57 mm, gave an impingement time of almost 40 minutes. The full test matrix with setup parameters is summarised in Section 2.4.

Figure 4: Smaller concrete test sample on top of base block

When each blowdown test was completed, a visual assessment of the incident surface of the sample was made and deformities were noted, e.g. scorch marks, ejected pieces of concrete. The sample surface for two samples was 3D laser scanned to provide more detailed information as to the depth and extent of the damage for a fibre containing vs. non-fibre containing sample.

A series of post-test material analyses were carried out to assess whether the jet impingement had degraded the samples at the microstructure level. Cores (150 mm diameter) were extracted from two of the test samples and the following tests were carried out:

- Compressive strength – according to BS EN 12390 standard [12]. When subjected to high temperatures, concrete can undergo physicochemical changes both during the heating process and the cooling process, which changes the uniformity of the concrete and can reduce compressive strength as a result.

- Thermal conductivity – as per BS EN 12664 standard [13]. When concrete is subjected to heating, it has been found that the thermal conductivity declines with increasing temperature due to the moisture loss and the change of permeability at elevated temperature [14]. During this process it is expected that there will be a migration of the moisture and a pore pressure increase, i.e. pressure in the voids of the concrete, generated by water evaporation. This may ultimately result in a mass loss due to loss of moisture.

- Ultrasonic pulse velocity testing – according to BS EN 12504 standard [15]. The time of travel of an ultrasonic pulse passing through the concrete is measured. Comparatively higher velocity is obtained when the concrete quality is good in terms of density, uniformity, homogeneity, e.g. even aggregate distribution, non-collapsed pores. A pulse velocity measurement of >4 km/s is generally considered as an indicator of good concrete quality.

Road surfacing sample – visual assessment

A section of pipework with a 90° bend was added for the release onto the road surfacing sample, the aim being to extend and orient the release downwards, as would be the case for a release from a car fuel tank relief device. The stand-off distance between the nozzle and road surfacing material was 100 mm, approximately. The ignition light was placed adjacent to the jet incident location. The jet release was imaged from a side on position using a general camera and from an elevated view using a drone camera.

2.4 Summary of test matrix

Six jet fire experiments were conducted in total; the test matrix is summarised in Table 1.

Table 1: Summary of test matrix, including selected nozzle sizes, standoff distances of the test pieces and visualisation and analytical techniques used

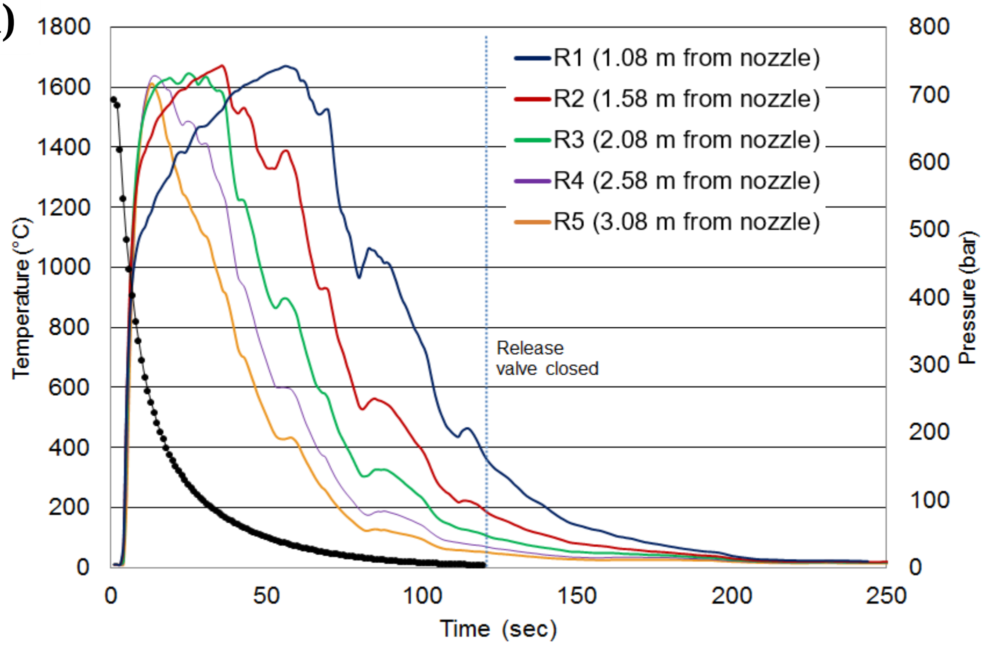
Test ID	Notes	Conditions			Measurement
		Volume (L)	Nozzle diameter (mm)	Sample stand-off (m)	
1	Free jet	49	2.1	n/a	Jet axial temperature
2	High strength concrete (no fibres)	98	2.1	1.06	Visual assessment, 3D laser scan and material analysis of sample
3	High strength concrete (no fibres)	98	2.1	2.24	Visual assessment
4	High strength concrete with PP fibres	98	2.1	1.06	Visual assessment, 3D laser scan and material analysis of sample
5	High strength concrete with PP fibres	98	0.57	1.11	Visual assessment
6	Asphalt road surfacing	98	2.1	0.1	Visual assessment

3.0 RESULTS

3.1 Unimpeded jet release – jet axial temperature

Figure 5 shows the temperature measurements from the five thermocouples and the pressure measurements from the vessel as the release progressed. R1 represents the thermocouple closest to the nozzle/release point. As seen in the graph, temperatures of up to 1650 °C were measured, with the hottest temperatures reached at distances of over 3 m from the release point. R1 does not reach its highest temperatures until almost 70 seconds into the release. It is expected that this is the case, as, at the beginning of the release, R1 is in a fuel-rich portion of the jet and thus, does not experience a stoichiometric mix. A thermal camera, placed side on, aided qualitative visualisation of the jet, as shown in Figure 5.

(a)



(b)

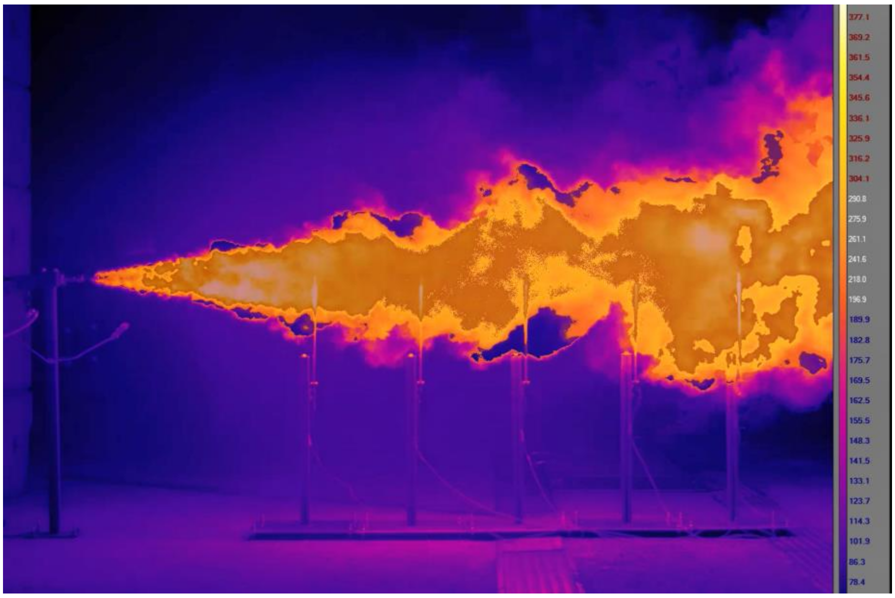


Figure 5: 700 bar blowdown, 49 L volume, 2 mm nozzle ignited release. Type 'R' thermocouple placed along the axial direction of the jet (a) plot of temperature readings from each thermocouple and vessel pressure data (b) thermal image of release, i.e. at 25 seconds into release approx. Camera field of view wasn't wide enough to capture full extent of jet.

3.2 Impeded jet release – concrete samples

Four concrete samples were tested (Tests 2-5 in Table 1), two containing polypropylene (PP) fibres, and two without fibres. Table 2 summarises the test conditions of the releases for each concrete sample and the visual result following impingement from the jet.

Table 2: Jet impingement onto concrete samples; test parameters and visual results following test. PP = polypropylene

Test ID	Nozzle diameter (mm)	Standoff distance (m)	Result
Test 2 **High strength concrete – No PP fibres**	2.1	1.06 (3.5 mins impingement approx.)	Spalling across entire surface, deepest spall occurred at centre of sample. See Figure 6a for laser surface scan.
Test 3 **High strength concrete – No PP fibres**	2.1	2.24 (1.5 mins impingement approx. – due to greater standoff distance)	Spalling evident across the majority of the sample surface. Depth and extent of spall not as severe as in Test 2, where sample was closer to the release nozzle.
Test 4 **High strength concrete – With PP fibres**	2.1	1.06 (3.5 mins impingement approx.)	Minimal spalling occurred, scorch mark resulted. See Figure 6b for laser surface scan.
Test 5 **High strength concrete – With PP fibres**	0.57	1.11 (40 mins impingement approx.)	No spalling occurred, larger scorch mark than that of Sample in test 3

It was observed that spalling occurred in both of the non-PP fibre containing concrete samples (Test 2 and 3), even when one sample was placed at a further stand-off distance from the nozzle giving a shorter impingement time, i.e. Test 2 sample was set at 1.06 m away, whilst Test 3 sample was set at 2.24 m away (the depth of spall was less than that of Test 2).

The surface of the sample in test 2 was laser scanned, as shown in Figure 6, to assess the depth of spalling, which was found to be approximately 30 mm at its deepest and occurred in the centre of the sample. This is not unexpected as this would be the area suffering the most sustained impingement from the jet flame and would have less opportunity to relieve stresses from thermal expansion compared to the edges.

The samples containing the polypropylene fibres on the other hand (Test 4 and 5), whilst sustaining a scorch mark in each case, exhibited minimal to no spalling. In the case of the longer impingement time of 40 minutes (achieved using a smaller 0.57 mm nozzle), a larger and more pronounced scorch mark resulted (diameter of the scorch mark was approximately 650 mm), however no spalling was observed (Test 5). The surface of the sample in Test 4 was laser scanned as a comparison with the non-PP fibre containing sample with the same test conditions, i.e. Test 2 with nozzle size of 2.1 mm and standoff distance of 1.06 m.

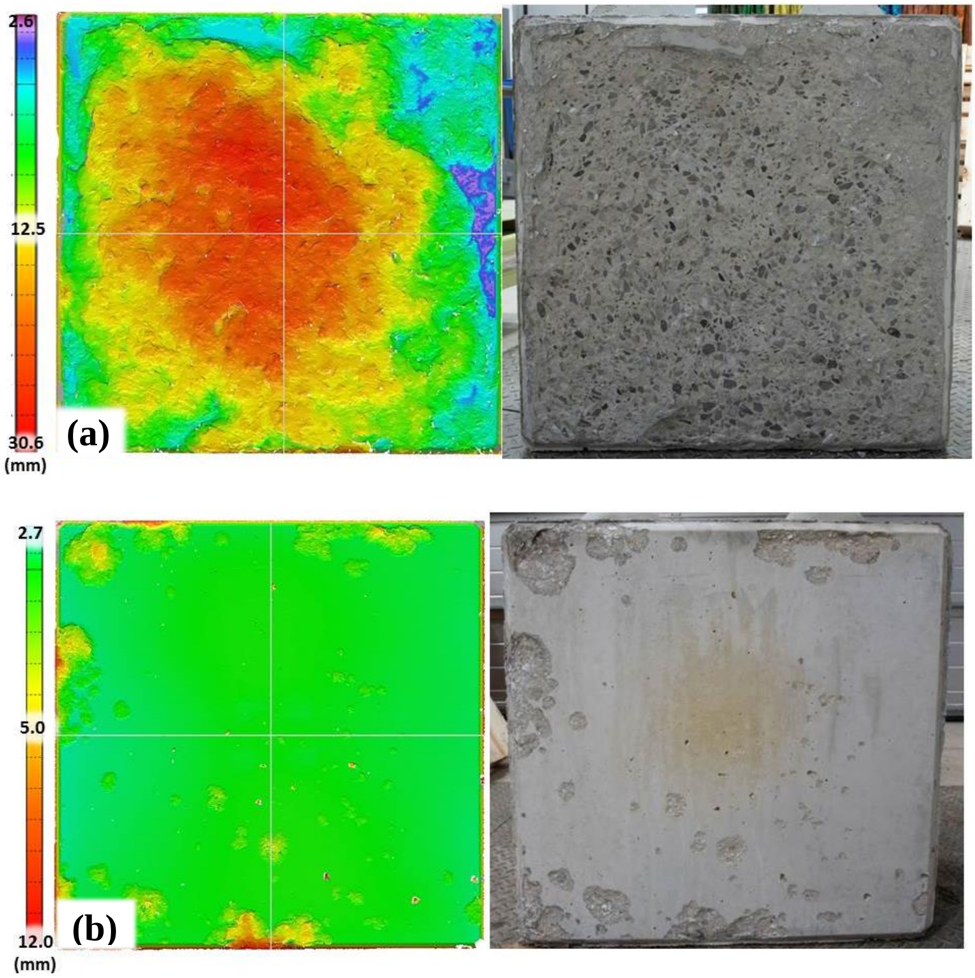


Figure 6: Laser scan and visual image of surface of (a) test 2, no PP fibres, and (b) test 4, with PP fibres. Release conditions for both, 700 bar, 98 L, 1.06 m standoff, 2 mm nozzle. PP= polypropylene

The results from the post-test material analysis are shown for each sample in Table 3.

Table 3: Post-test material analyses; where a sample was available, the same measurements were made on a non-jet impinged sample to allow for comparison of effects of the jet.

	Fire impinged sample – no PP fibres (Test 2)	**Comparative unimpinged sample – no PP fibres (Test 2)**	**Fire impinged sample – PP fibres (Test 4)**	**Comparative unimpinged sample – PP fibres (Test 4)**
Core compressive strength (N/mm^2)	54.9	55.3	50.1	No test core available
Thermal conductivity ($W{\cdot}m^{-1}\,K^{-1}$)	0.649 ± 2.5%	0.792 ± 2.5%	0.933 ± 2.5%	0.614 ± 2.5%
Pulse velocity (km/s)	4.79	4.65	5.00	4.62

The results show that the compressive strength of the non-fibre containing samples does not appear to have been affected as a result of the fire impingement. A value of 55.3 N/mm^2 was recorded for the non-fire impinged sample vs. 54.9 N/mm^2 for the fire impinged sample. The compressive strength for the PP containing sample was measured to be slightly lower than that of the non-fibre containing samples. This is not unexpected as polypropylene fibres would not contribute to the compressive strength in the same way as cement or aggregate. A comparative non fire impinged PP fibre sample was not available.

Regarding the thermal conductivity measurement, the results as shown in Table 3 suggest a slightly lower thermal conductivity on the fire impinged Test 2 sample (containing no PP fibres) relative to its non-fire impinged sample. This result is in line with the theory of having a lower thermal conductivity with declining moisture content [16]. The Test 4 sample, i.e. (PP fibre containing) on the other hand, displayed the opposite behaviour, with the fire impinged sample having a higher thermal conductivity than the non-fire impinged comparison. This may be the result of the solid to liquid phase change that will occur when the polypropylene fibres are heated during the jet fire. Upon cooling, these may have left heat conduction channels in the melted fibres that would increase the thermal conductivity of the sample overall. On a general note, at ambient temperature it is expected that the presence of PP fibres would, by their nature, provide increased thermal resistance, which would translate as a lower thermal conductivity than the non PP fibre containing sample. However all in all the changes are minimal.

For the ultrasonic scanning, three pulse velocity measurements were made for each sample; the average for each is shown in the last row of Table 3. All samples had velocities of greater than 4 km/s, which, according to the terms of the testing standard, would indicate very good to excellent quality concrete. The cores from the fire impinged samples had slightly higher pulse velocity readings than their corresponding, non-jet impinged samples, but the differences are minimal. The results indicate that the jet impingement and resultant spalling has had little effect on the uniformity of the concrete, i.e. had not introduced structural deformities such as cracks or voids. It should be noted that this technique is better at picking up deformities of the order of 100 mm, and relatively small defects have little effect on transmission. Thus, the observed depth of spall, i.e. up to 30 mm could possibly have been a surface only, relatively small defect that would have little or no effect on transmission times. From a structural point of view, it is thought that defects of this magnitude are probably of minor engineering importance [15].

3.3 Impeded jet release – Road surfacing sample (one test)

The duration of the jet release onto the road surfacing sample (Test 6 in Table 1), was approximately 40 seconds, from 700 bar down to 212 bar. Figure 9 shows still images to illustrate the jet progression at intervals over the 40 second period. The 0 second image shows the setup before the hydrogen jet was introduced, the 40 second image shows the setup immediately after the jet release valve had been closed. During the release, the resultant flames did not appear to contain partially combusted carbon products, i.e. often evident as black smoke, as may be expected during combustion of a bituminous sample, suggesting that it is only the hydrogen providing the fuel source during the blowdown. The flames are visible; visible orange flames were also observed during the horizontal impeded jets, i.e. onto the concrete samples. Parts of the sample were forcibly ejected during the release. At the 40 second period, once the jet was quenched, black smoke was observed emanating from the sample, however the sample did not progress to sustained combustion. In the central location of the sample, a well had been formed at the location where the jet directly impinged onto the sample. The melting point of road surfacing material will vary depending on the grade of bitumen binder used but will typically soften between 50 and 80 °C.

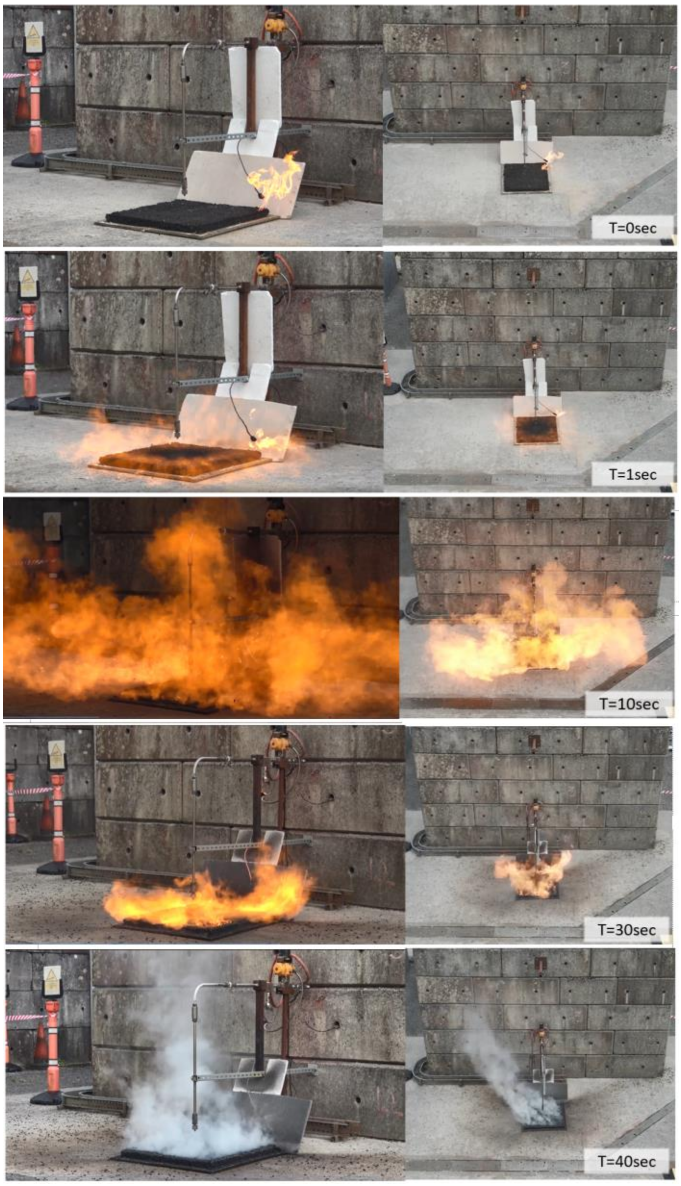


Figure 7: Still images from video recording of jet release onto road surfacing sample. Images show jet progression over the 40 second blowdown

4.0 CONCLUSIONS

In terms of the erosive effects on concrete, the testing and analysis indicated that a short duration hydrogen jet impingement, i.e. 4 kg hydrogen inventory, 700 bar release through a 2 mm nozzle lasting for 3 mins 45 secs approximately, appeared to generate surface spalling only (to a depth of 30 mm at its worst). The post-test material analysis indicated that the jet impingement did not appear to have weakened the concrete or introduce appreciable pore deformation or defects into the concrete itself. The presence of polypropylene fibres in some samples, a known mitigation strategy for spalling, proved effective for a hydrogen jet also, with no spalling observed on those samples.

It is worth commenting that these test results are specific to this jet fire setup used and the composition of the sample itself and thus the results are not necessarily directly transferable to any arbitrary sample. For example, ventilation will affect the magnitude of the resultant temperature of the burning hydrogen jet, compression/external load on the sample will affect its propensity to spall [17]. Also, it was found that larger samples with the same concrete composition as smaller samples were more likely to spall due to the added load generated by the sample bulk itself [18]. Therefore, it is recommended that a wider range of test conditions and material properties are investigated.

The duration of a hydrogen release would be limited by the inventory of the vehicle, and the development and duration of a representative fire curve for a hydrogen jet fire would be of the order of a few minutes rather than 1-2 hours, as is typical of the standard fire curves. On the basis of this test programme, it is suggested that though hydrogen has the potential to reach greater temperatures and faster than that of a hydrocarbon fire, the resultant fire by itself, may not contribute additional risk in terms of erosion of structural materials.

Acknowledgement

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 826193. The contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

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