Calibrating Washington Hydraulic Fracture Apparatus

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The Washington Hydraulic Fracture Test (WHFT) was developed as a part of the Strategic Highway Research Program (SHRP) as a rapid method to identify aggregates susceptible to D-cracking. WHFT relies on the pressure differential between the inside and outside of the aggregate pieces to cause D-cracking susceptible pieces to fracture. D-cracking susceptible aggregates sources are identified as those that produce more fracturing than non–D-cracking susceptible sources. Agencies will be able to establish their own criteria for threshold fracturing, which defines D-cracking. Experience, however, suggests that a hydraulic fracture index of approximately 60 to 80 or lower indicates a D-cracking susceptible aggregate. Though the procedure was found to be fairly reliable for a large range of aggregate sources, the critical parameters of the test procedure were not determined during SHRP. Specifically, the critical pressure release rate believed to be responsible for the WHFT mechanism was not determined. Current research for the Michigan Department of Transportation is investigating the applicability of the WHFT for Michigan. Included in the work plan is the determination of what parameters were necessary to ensure that equipment remained in calibration. The important parameters necessary for calibration are described and the sensitivity of those parameters determined. Modifications were made to the WHFT apparatus and to the testing procedure so that a range in the amount of fracturing in the aggregate was produced. Measurements of the pressure-time history during pressure releases were taken, and pressure release rates determined from these pressure-time histories were compared with the amount of fracturing produced. The amount of fracturing produced was found to be sensitive to a pressure release rate at very short time durations (typically less than 0.02 sec). This information can be used to specify the pressure release rate at a given time duration so that agencies can be assured that multiple copies of WHFT equipment produce the same test results.

The Washington Hydraulic Fracture Test (WHFT) was developed as a part of the Strategic Highway Research Program (SHRP) as a rapid method to identify aggregates susceptible to D-cracking. WHFT requires 8 working days to determine the D-cracking susceptibility. The normally used identification procedure (Rapid Freezing and Thawing, AASHTO T161, ASTM C 666) requires 5 weeks to 5 months. WHFT relies on the pressure differential between the inside and outside of the aggregate pieces to cause D-cracking susceptible pieces to fracture. D-cracking susceptible aggregates sources are identified as those that produce more fracturing than non–D-cracking susceptible sources. Although agencies are likely to establish their own criteria for a fracturing threshold, experience suggests that a hydraulic fracture index (HFI) of approximately 60 to 80 indicates a D-cracking susceptible aggregate (1–4). Though the procedure was found to be fairly reliable for a large range of aggregate sources, the critical parameters of the test procedure were not determined during SHRP. Specifically, the critical pressure release rate believed to be responsible for the WHFT mechanism was not determined.

Current research for the Michigan Department of Transportation is investigating the applicability of WHFT for Michigan adoption. Included in the work plan is the determination of what parameters are necessary to ensure that equipment remains in calibration. The purpose of the work described in this paper is to identify the important parameters necessary for calibration and to determine the sensitivity of those parameters.

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BACKGROUND

Occurrence of D-Cracking

D-cracking is the term used to describe the distress in concrete that results from the disintegration of coarse aggregates after they have been subjected to repeated cycles of freezing and thawing in the presence of water (*5*). D-cracking is observed most often in pavements and is associated with portions of the concrete exposed to moisture intrusion from multiple directions such as pavement joints where water can intrude from both the top and the bottom of the concrete slab, as well as the vertical joint face. D-cracking is often first noticed at the intersections of longitudinal and transverse joints, which provide mutually perpendicular sources of intrusion. Although the occurrence of D-cracking is associated with the coarse aggregate used to make the concrete, aggregate size also has an effect. Often, the D-cracking susceptibility of an aggregate source can be reduced by reducing the maximum size of the aggregate (*6,7*).

Identification of D-Cracking Susceptible Aggregates

D-cracking has been known to exist since the 1930s (*6*). However, a fast, reliable, reproducible, easily performed, and inexpensive test for identifying aggregates susceptible to D-cracking has not been developed. The most commonly used method for identifying D-cracking susceptible aggregates is Rapid Freezing and Thawing (AASHTO T161, ASTM C 666). In this method, concrete prisms or cylinders are prepared from the coarse aggregate in question. The specimens are cured (14 days or longer) and subjected to repeated cycles of freezing and thawing. Periodic measurements of relative dynamic modulus or length change, or both, are made. The test is concluded when either the specified number of cycles has been achieved (generally 300 or 350) or failure criteria have been reached (generally a relative dynamic modulus of 50 percent or an expansion of 0.1 percent). This procedure can take from 5 weeks to 5 months, depending on the duration of the curing period and the length of the freezing and thawing cycle (*6,8*).

Washington Hydraulic Fracture Test

Because rapidly identifying D-cracking susceptible aggregates is important, it was included as an objective in the recently completed work sponsored by SHRP (*1*). The test procedure developed under SHRP is WHFT and requires only 8 working days to complete. The test method is based on the assumption that the hydraulic pressures expected in concrete aggregates during freezing and thawing can be simulated by submerging oven-dried sample aggregates in water and then subjecting them to high pressures. As the external chamber pressure is increased, the water penetrates into increasingly smaller pores of the aggregate and pressurizes the air in the aggregate pores. When the external pressure is rapidly released, the air compressed within the pores pushes the water back out, thereby simulating hydraulic pressures generated during freezing. The aggregate fractures if the pressure in the pores cannot be dissipated quickly and the aggregate is unable to elastically accommodate the high internal pressure (*1–4*).

In practice, the procedure involves filling a pressure chamber with oven-dried aggregate. The chamber is closed and filled with water. Care is taken to ensure that all air bubbles are removed during the filling process, because air bubbles would affect the pressure release. After filling, the chamber is pressurized for 5 min using a compressed nitrogen source, the pressure is rapidly released, and the chamber is refilled for 1 min. The chamber is then pressurized for 2 min, the pressure is released, and the chamber is refilled. This 2 min pressurization, pressure release, refill cycle is repeated for 10 pressurizations. The aggregate is then removed from the chamber and oven dried; the pieces are counted to determine the increase in the number of pieces. The ratio of the number of new pieces to the number of original pieces is termed the percentage of fracturing. The test is concluded after a total of 50 cycles of pressurization (5 days of pressurization), and an HFI is calculated as the number of cycles of pressurization necessary to produce 5 percent fracturing. If 5 percent fracturing is achieved during the 50 cycles of pressurization, HFI is determined as an interpolation to the nearest integral number of cycles to produce the 5 percent fracturing. If 5 percent fracturing is not achieved in the 50 pressurization cycles, HFI is determined by extrapolating a line from the origin through the percentage of fracturing at 50 cycles. The HFI is the extrapolation of this line to determine the integral number of cycles to produce 5 percent fracturing. Details of the testing procedure are given elsewhere (*1–4*).

Chamber Modification and Calibration

Initial development of the WHFT apparatus used a pressure chamber having inside dimensions of 255 mm in diameter by 51 mm deep. Tests were run at both 7240 and 7930 kPa (1,050 and 1,150 psi). The percentage of fractures versus the number of cycles of pressurization for a D-cracking susceptible gravel is shown in Figure 1 for both 7,240 and 7930 kPa. The 7930 kPa pressure produced more fracturing in the D-cracking susceptible aggregate and was used for further WHFT work because this higher pressure did a better job of separating D-cracking from non–D-cracking susceptible aggregates based on the amount of fracturing (*1–3*).

Variability results for the WHFT procedure suggested that a specimen size of 600 to 800 pieces was necessary to reduce the coefficient of variation of the HFI value to below 10 percent (*1*). The 51-mm deep chamber typically held about 150 to 200 pieces in the 19- to 32-mm size range. This meant that four replications of the test had to be obtained to achieve an acceptable variation. Attempts were made under SHRP to produce a larger WHFT apparatus capable of accommodating an 800-piece specimen of 19- to 32-mm aggregate in a single replication. Calibration work focused on duplicating the pressure-time history of the original WHFT apparatus. A pressure chamber with the same internal diameter, but 255 mm long, was acquired, and changes were made in the fittings and

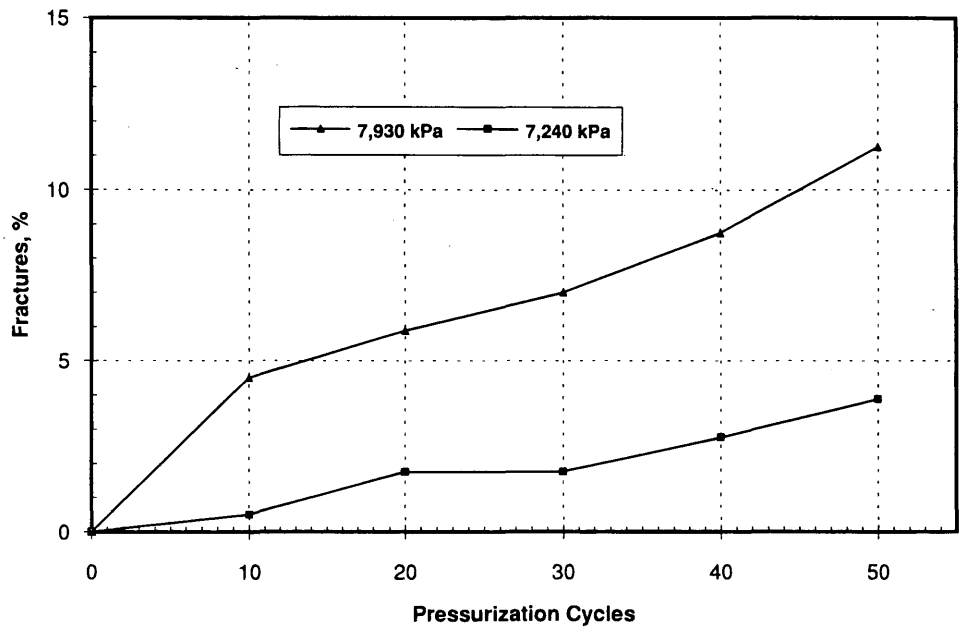

FIGURE 1 Percentage of fractures versus the number of cycles for initial pressures of 7240 and 7930 kPa initial pressures (*1,2*).

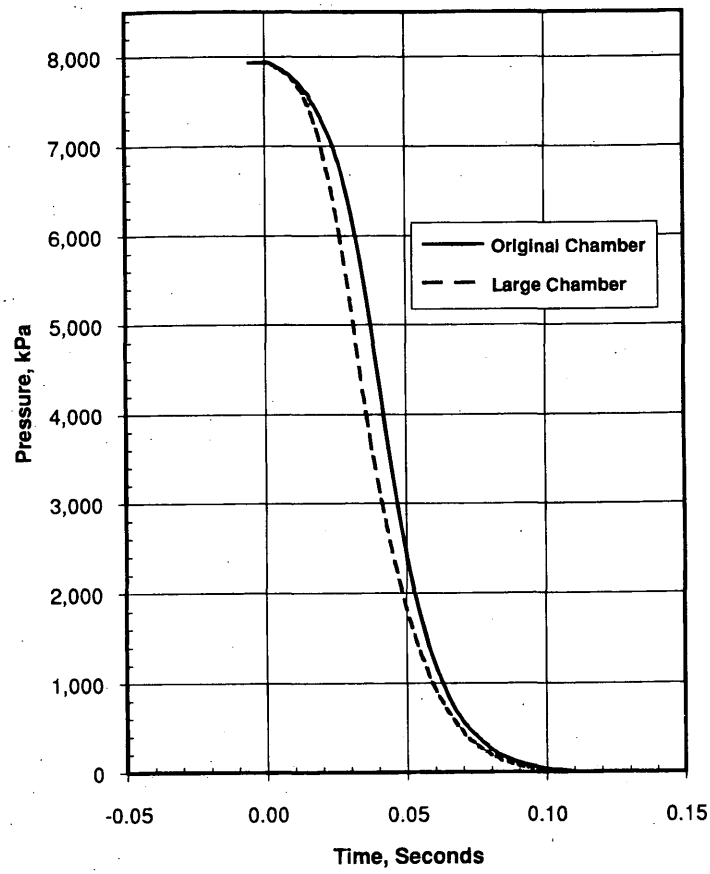

FIGURE 2 Pressure release histories for original and large apparatus (*1*).

valves to duplicate the pressure-time history of the original chamber. Figure 2 shows the pressure-time histories for a single pressure release of the original chamber and the large chamber, both pressurized to 7930 kPa (1,150 psi) (*1*). As can be seen, the pressure-time curves look similar though not identical. It was believed that the nearly identical pressure-time histories would produce similar results when aggregates were tested, though this aggregate testing comparison was not included in the work by SHRP.

EXPERIMENTAL PROCEDURES

Two procedures were used in the work described in this paper: calibration of the testing apparatus and actual testing of the aggregate.

Calibration

For the calibration procedure, the apparatus was fitted with a piezoelectric pressure transducer of suitable capacity. Output from this transducer was digitally recorded at a sampling rate of 4,096 hz. The apparatus was pressurized, and the pressure was released in the same manner as described previously, except that no aggregate was placed in the chamber. The pressure-time history from each pressure release was analyzed to determine the fastest pressure release rates for given time durations (e.g., .002 sec, .004/sec, .006 sec, and so on). For a given time duration, the release rate was calculated as the slope of a line through the endpoints of a piece of the pressure-time history curve that incorporates that time duration. Release rates at each time duration were averaged for 10 consecutive pressure releases (described in the WHFT procedure) and a plot of release rate versus time duration was produced.

Repetition of the pressure release rate measurement on consecutive days showed variations in release rate at short time durations of approximately 10 percent. Release rate plots in the analysis section of this paper are averages of 2 or more days of measurements.

WHFT

Aggregate testing using the WHFT procedure with various combinations of chamber configuration and initial pressures was conducted using a limestone from Michigan, previously identified as being D-cracking susceptible. Material in the size range of 19 to 25 mm was used. Early in the testing program (*9*), it was discovered that some fracturing in the 51-mm deep chamber was caused by physical contraction of the chamber after depressurization. This fracturing was eliminated in the testing program described next by attaching a 0.8-mm thick rubber liner to the inside faces of the end plates of the pressure chamber.

TESTING PROGRAM

Preliminary Testing

As stated previously, the purpose of the work described in this paper is to identify the important parameters necessary for calibration of the WHFT equipment. Initial test development work (*2*) suggested that a critical pressure-time history exists that defines WHFT. This pressure-time history appeared sensitive to initial chamber pressure. The critical parameters of the pressure-time history probably consist of a critical pressure release rate and a duration of time for which this release rate must be maintained. Measurements of the pressure-time histories for the original chamber at both 7240 and 7930 kPa initial pressures are shown in Figure 3. The initial pressure difference can easily be seen, but otherwise the slopes of the curves look quite similar. To determine whether the higher initial pressure allowed a given pressure release rate to be maintained for a longer duration of time, the release rates versus time duration relations were determined. These are shown in Figure 4 for the initial pressures of 7240 and 7930 kPa. The use of the lower pressure (7240 kPa) resulted in lower pressure release rates for all time durations.

Other work (*1*) developed a large WHFT apparatus that produced similar, but not exact, pressure-time histories. Calibration tests were performed on both the original WHFT apparatus and the large apparatus. The results are shown in Figure 5. It can be clearly seen that the large chamber gave consistently low release rates for an initial pressure of 7930 kPa for time durations of up to about 0.07 sec. Calibration tests were also performed on the large apparatus using an initial pressure of 8270 kPa to see whether this improved the pressure release rate. This result is also shown in Figure 5. Although the pressure release rate increased slightly, it did not increase to the level of the release rate for the original apparatus at the standard 7930 kPa initial pressure until the time duration exceeded about 0.05 sec. Release rates for the large apparatus at higher pressures were analyzed, but these were also low at short time durations when compared with the release rate of the original chamber. This suggested that the large chamber configuration had reached the maximum release rate possible with the existing fitting and valve configuration.

Apparatus Modification and Upgrading

As mentioned previously the large apparatus appeared to be limited in terms of achievable release rate by fitting and valve configurations. To achieve higher release rates in the large apparatus, it was modified by using larger size fittings and a larger diameter valve through which the pressure was released. It was believed that these attempts at reducing the fluid flow resistance would increase the pressure release rates. This new large apparatus is hereafter referred to as the "modified large apparatus."

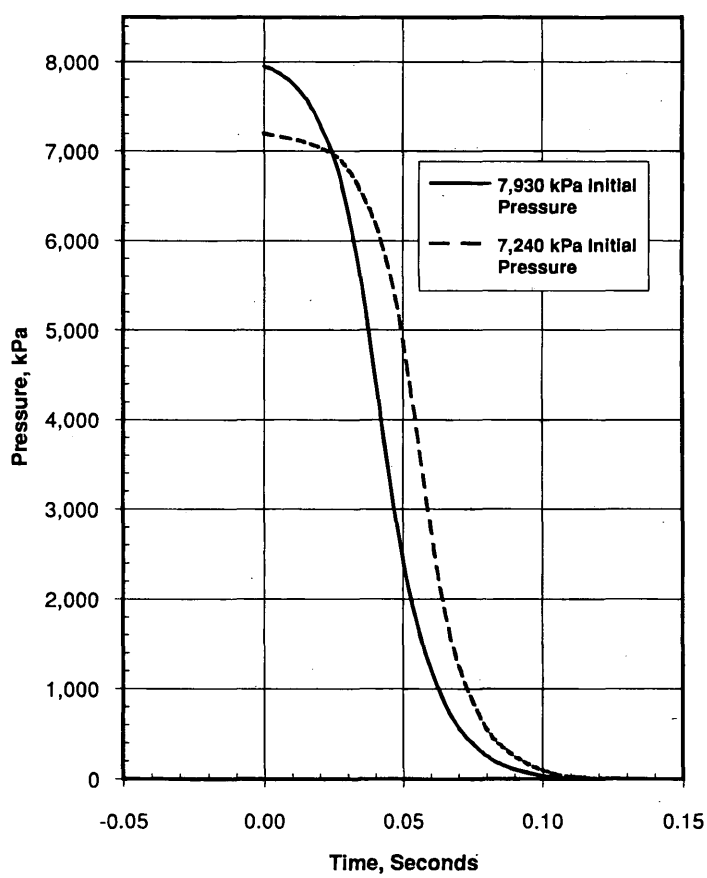

FIGURE 3 Pressure release histories for original apparatus at both 7240 and 7930 kPa initial pressures.

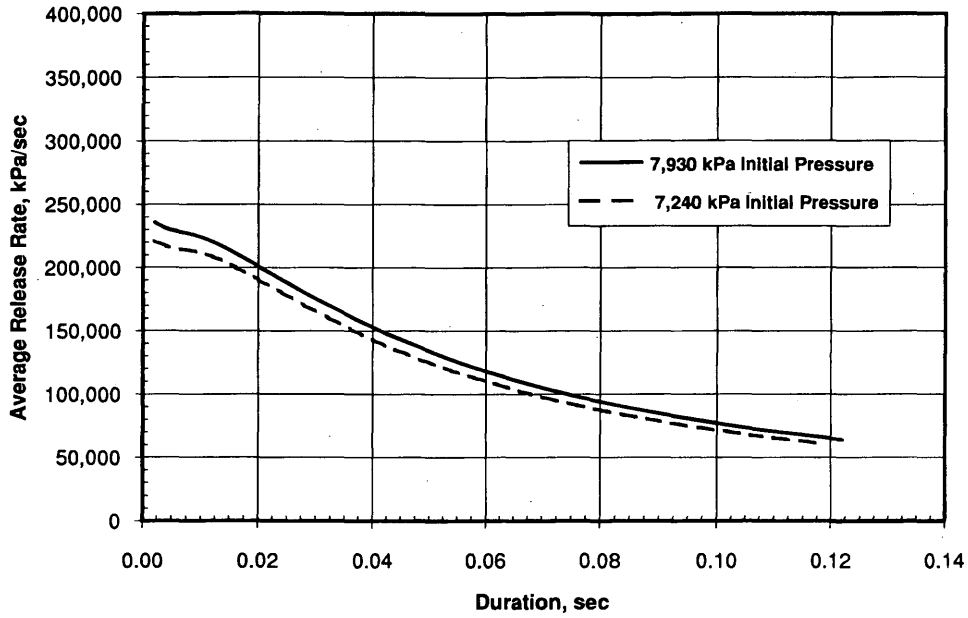

FIGURE 4 Pressure release rates for original apparatus at both 7240 and 7930 kPa initial pressures.

Also, during testing with the original chamber, problems with maintenance of the pressure-release valve were encountered. This valve was a plug-type valve with o-ring seals that frequently required replacing. The plug-type valve was replaced with a ball-valve having a larger internal bore. To reduce operated-related release rate variability, an electro-pneumatic actuator was added to the pressure.release ball-valve. This addition dramatically increased the release rate because the actuated valve was able to open much faster than a hand turned valve. The original apparatus with the ball valve and electro-pneumatic actuator will be referred to as the "upgraded original apparatus."

Calibration testing was conducted on the upgraded original apparatus at initial pressures of 7240, 7930, and 8620 kPa on the original apparatus at 7930 kPa. Testing was also conducted on the large apparatus at an initial pressure of 8270 kPa and on the modified large apparatus at initial pressures of 7930 and 8270 kPa. In some instances, these calibration tests were performed by a different operator from the one conducting the preliminary testing reported.

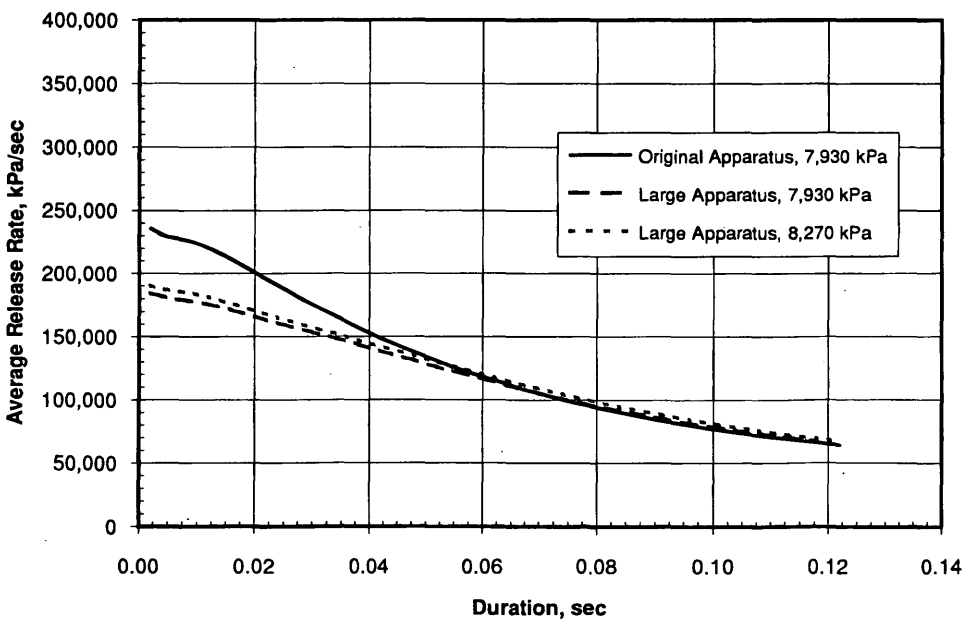

FIGURE 5 Pressure release rates for original and large apparatus.

Although this had no effect on the results for the upgraded original apparatus because of the pressure release rate being controlled by the electro-pneumatic actuator, a different release rate was produced in the manually released original apparatus. All results presented in the remainder of this paper are for the same operator doing the release-rate testing and the aggregate testing for a given configuration.

Aggregate testing with the previously mentioned configurations was also conducted. Testing in the modified large apparatus consisted of a single specimen of at least 800 pieces for each initial pressure. Testing in the original apparatus and upgraded original apparatus consisted of two specimens of at least 200 pieces each for each initial pressure. The results of the replicate specimens were combined for presentation of the results.

RESULTS

Figure 5 suggests that, to compare release rates for different configurations, the time duration for the comparison must be determined. A time duration of 0.01 sec was chosen for the presentation of release rate results. This time duration is short enough to provide good separation between the various release rate curves (as in Figure 5) while being long enough to permit sufficient data points to have been collected at the 4,096 Hz sampling rate so that a reliable measurement of release rate could be determined.

Release rate results at a time duration of 0.01 sec are shown in column 3 of Table 1 for the various configurations tested. The upgraded original apparatus in all cases had higher release rates than the original apparatus. This is probably the result of the larger bore of the ball-valve plus the faster valve turning with the actuator as compared with the manually operated plug-valve on the original apparatus. The modifications to the large apparatus, which included both a larger bore valve and a simplified plumbing arrangement, allowed a small increase in release rate.

HFI values from aggregate testing are shown in column 4 of Table 1. As can be seen, a range of HFI values were produced for the test aggregate by the various test configurations and initial pressures. Previous work (*1*) suggests that for the sample sizes tested, a coefficient of variation of 10 to 15 percent could be expected. The variation in HFI results is much higher than that. A standardization of the apparatus configuration is necessary to produce reliable WHFT results.

ANALYSIS

Comparing the HFI results in column 4 of Table 1 with the release rates shown in column 3 suggests that release rate alone is not the only factor in calibrating WHFT equipment to produce similar results. Figure 6 is a plot of the release rate at 0.01 sec duration versus chamber pressure. HFI values are plotted and labeled. This graph suggests that fracturing (lower HFI values) is sensitive to both release rate and chamber pressure. At release rates between 300 000 and 400 000 kPa/sec, the fracturing decreased for initial chamber pressures both above and below 7930 kPa. At a release rate of about 210 000 kPa/sec, the fracturing decreased with a decrease in chamber pressure from 8270 to 7930 kPa. No data are available for higher chamber pressures at a release rate of 210 000 kPa/sec. Below a release rate of 200 000 kPa/sec, the fracturing was reduced for both chamber pressures tested.

Figure 6 suggests that there is an optimal combination of release rate and chamber pressure necessary to maximize fracturing. The minimum release rate for producing fracturing appears to be about 210 000 kPa/sec for a 0.01 sec duration. This is for a chamber pressure of 8270 kPa. Figure 6 also suggests that as the release rate is increased to about 300 000 kPa/sec at 0.01 sec duration, the acceptable chamber pressure should be in the range of about 7930 to 8270 kPa. Because Table 1 indicates that the release rate is sensitive to the initial chamber pressure for some equipment configurations, calibrating the equipment to produce the desired chamber pressure and release rate combination is necessary.

CONCLUSIONS AND RECOMMENDATIONS

The testing described has looked at various configurations for apparatus to perform the WHFT procedure in an attempt to determine

TABLE 1 Release Rate and HFI Results

Apparatus Configuration	Initial Pressure (kPa)	Release Rate at 0.01 sec. (kPa/sec.)	HFI
Original	7,930	184,400	104
Upgraded Original	7,240	318,300	180
Upgraded Original	7,930	319,100	71
Upgraded Original	8,620	360,400	109
Large	8,270	183,300	104
Modified Large	7,930	213,600	206
Modified Large	8,270	211,700	66

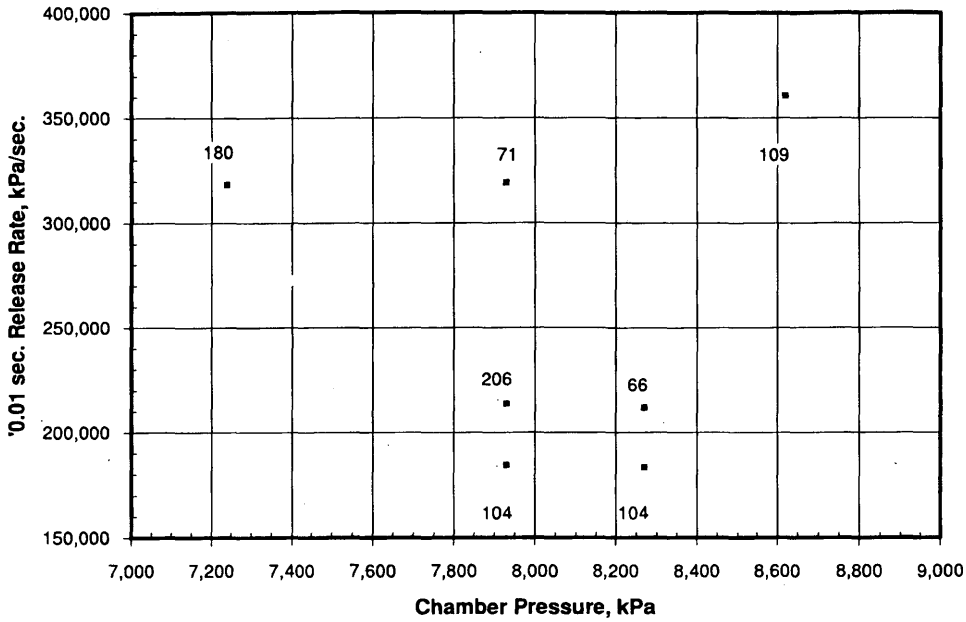

FIGURE 6 HFI as function of release rate and chamber pressure.

how to calibrate the equipment to produce consistent results. The WHFT procedure has been shown to be sensitive to both pressure release rate at short time durations and initial chamber pressure, with an absolute minimum rate of 210 000 kPa at a duration of 0.01 sec and a chamber pressure of 8270 kPa necessary. A minimum release rate of 300 000 kPa/sec at a time duration of 0.01 sec with chamber pressures in the range of 7930 to 8270 kPa would probably be a more reasonable recommendation for chamber calibration. The effects of 0.01 sec duration release rates considerably in excess of 400 000 kPa/sec have not been determined at this time.

To validate and extend the work presented in this paper, the following is recommended:

- Conduct testing on additional aggregate sources (both D-cracking susceptible and non–D-cracking susceptible) at various apparatus configurations and chamber pressures producing higher release rates to determine what, if any, maximum release rate is necessary to prevent excessive fracturing.
- Conduct testing on additional aggregate sources (both D-cracking susceptible and non–D-cracking susceptible) using the upgraded original apparatus at a more closely spaced range of pressures to better identify the optimal release-rate and chamber-pressure combinations.

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REFERENCES

1. Janssen, D. J., and M. B. Snyder. *Resistance of Concrete to Freezing and Thawing*. SHRP–C–391. TRB, National Research Council, Washington, D.C., June. 1994.
2. Almond, D. K. *A Test for Identifying Aggregates Susceptible to Freeze-Thaw Damage*. M. S. thesis. Department of Civil Engineering, University of Washington, June 1990.
3. Almond, D. K., and D. J. Janssen. The Washington Hydraulic Fracture Test for Concrete Aggregates Exposed to Freezing and Thawing. Supplemental Paper. *Proc. 2nd CANMET/ACI International Conference on Durability of Concrete,* Montreal, Canada, Aug. 1991, pp. 265–293.
4. Janssen, D. J., and D. K. Almond. A Comparison of Four Aggregates Using the Washington Hydraulic Fracture Test. In *Transportation Research Record 1301,* TRB, National Research Council, Washington, D.C., 1991, pp. 57–67.
5. Schwartz, D. *NCHRP Synthesis of Highway Practice 134: D-Cracking of Concrete Pavements.* TRB, National Research Council, Washington, D. C., 1987.
6. Stark, D., and P. Kleiger. Effects of Maximum Size of Coarse Aggregate on D-Cracking in Concrete Pavements. In *Highway Research Record 441,* HRB, National Research Council, Washington D.C., 1973, pp. 33–43.
7. Traylor, M. L. Efforts to Eliminate D-Cracking in Illinois. In *Transportation Research Record 853,* TRB, National Research Council, Washington, D.C., 1982, pp. 9–14.
8. Marks, V. J., and W. Dubberke. Durability of Concrete and the Iowa Pore Index Test. In *Transportation Research Record 853,* TRB, National Research Council, Washington, D.C., 1982, pp. 25–30.
9. Alford, T. E. *Calibrating the Washington Hydraulic Fracture Test.* M. S. thesis. Department of Civil Engineering, University of Washington, June 1995.

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