Chapter 5. Tests Performed using 4-inch Diameter Filter Test Device

5.1. Introduction

A total of twenty-seven tests were conducted with the 4-inch diameter filter test device. The conditions examined in these tests are summarized in Table 5.1. Test 1 through Test 12 were pilot tests, conducted to determine the proper specimen fabrication techniques, to refine the instrumentation and data recording methods, and to examine the influence of the device orientation and flow direction on the test results.

The pilot tests were performed using the tap water in the laboratory as the source of water, controlling the pressure using a water pressure regulator. However, it proved not to be possible to maintain a constant pressure in this way. To overcome this difficulty a water tank pressurized with regulated air pressure was used as the source of water for subsequent tests. In all of the pilot tests, the crack width was 0.03 inches.

Table 5.1 Test summary of 4-inch filter test device

	Compaction Method	Crack width cw (inch)	Crack Oriendation / Flow Direction	Pressure Control	DAQ Measurement			Base Material	Filter Material	Filter Material Properties			
					Flow	Pressure	Video			fc (%)	w (%)	D_r (%)	γ_d (pcf)
Test 1	Standard Proctor Hammer	0.03	H / H	Direct Connection from Tap Water with Regulator	Not measured	Not measured	Not Monitored	Teton Dam Core	Ochoco Dam Filter	4	11.5	N/A	N/A
Test 2		0.03	H / H							4	11.5		
Test 3		0.03	V / H				Monitored			4	11.5		
Test 4		0.03	V / H							4	11.5		
Test 5		0.03	V / V							4	11.5		
Test 6		0.03	V / V						Pea Gravel	0	N/A		
Test 7		0.03	V / H			Measured			Fabricated Filter	0	5.6		111.4
Test 8		0.03	V / H							0	5.6		111.5
Test 9		0.03	V / V		Measured				Ochoco Dam Filter	0	12.3		109.9
Test 10		0.03	V / V							5	12.3		114.5
Test 11		0.03	V / V							10	12.3		110.1
Test 12		0.03	V / V							15	12.3		120.8
Test 13	Moist Tamping	0.03	V / V	Constant from Water Tank					Horsetooth Dam Filter	0	10	50	109.3
Test 14		0.06	V / V							0	10	50	109.3
Test 15		0.09	V / V							0	10	50	109.3
Test 16		0.03	V / V							0	10	70	113.7
Test 17		0.06	V / V							0	10	70	113.7
Test 18		0.09	V / V							0	10	70	113.7
Test 19		0.03	V / V							5	10	70	117.9
Test 20		0.06	V / V							5	10	70	117.9
Test 21		0.09	V / V							5	10	70	117.9
Test 22		0.03	V / V							15	10	70	123.2
Test 23		0.06	V / V							15	10	70	123.2
Test 24		0.09	V / V							15	10	70	123.2
Test 25		0.03	V / V							0	14	70	113.7
Test 26		0.09	V / V							15	14	46	123.2
Test 27		0.15	V / V							0	10	18	103.4

5.2. Sample Preparation

As mentioned earlier, the cross section of the 4-inch diameter filter test device is a truncated circle. The standard Proctor (ASTM D698) compaction hammer was used to compact the specimens in the filter test device. The segments of base and filter material were 3 inches high after compaction. The base material was compacted to 95% of the maximum density as determined by the standard proctor test, ASTM D698. The filter material was compacted to values of relative density varying from 18% to 70%. For density control, the thickness of every compaction lift was measured using the depth gauge shown in Figure 5.1.

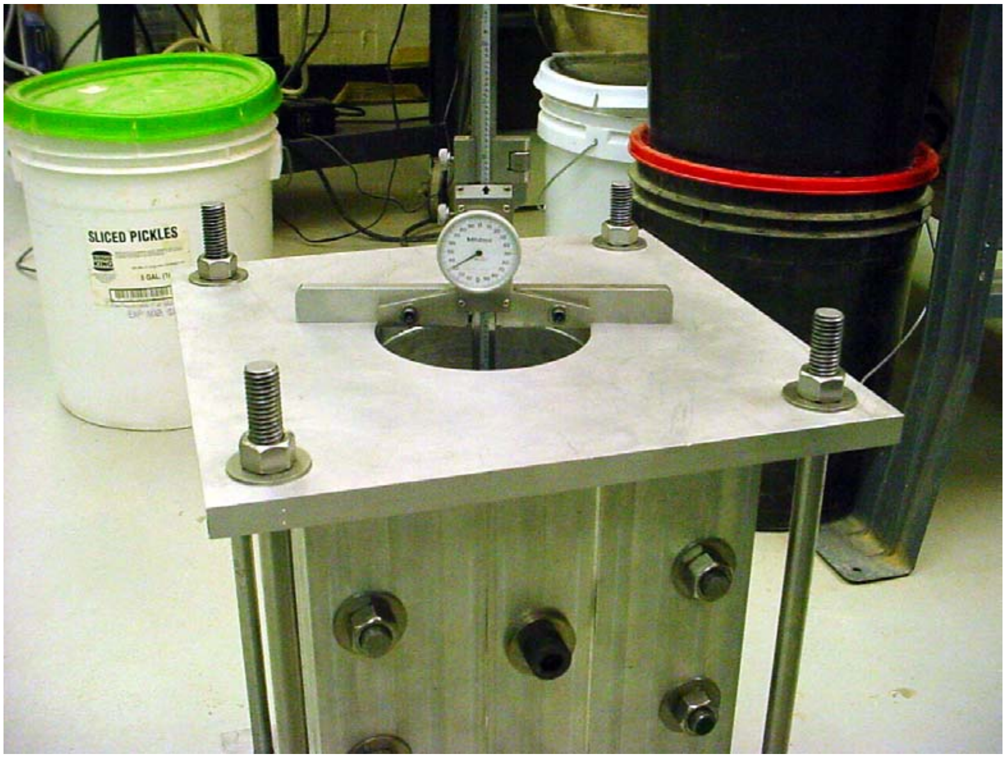


Figure 5.1 Measuring thickness of each layer by depth gauge

Figure 3.2(a) (in Chapter 3) shows a cross section through the 4-inch diameter filter test device. Compaction with void-forming plates inside the device produced samples with truncated circular shapes. The void-forming plates were removed after compaction. The void-forming plates extended over the filter and base material segments of the specimens. The closure plate was replaced by a clear plastic plate before testing so that particle movements could be observed during the tests. Figure 5.2 shows a perspective view of the 4-inch diameter filter test device. A longitudinal cross section through the device is shown in Figure 5.3. The detailed steps involved in assembly and preparation of a sample are explained in Appendix A.

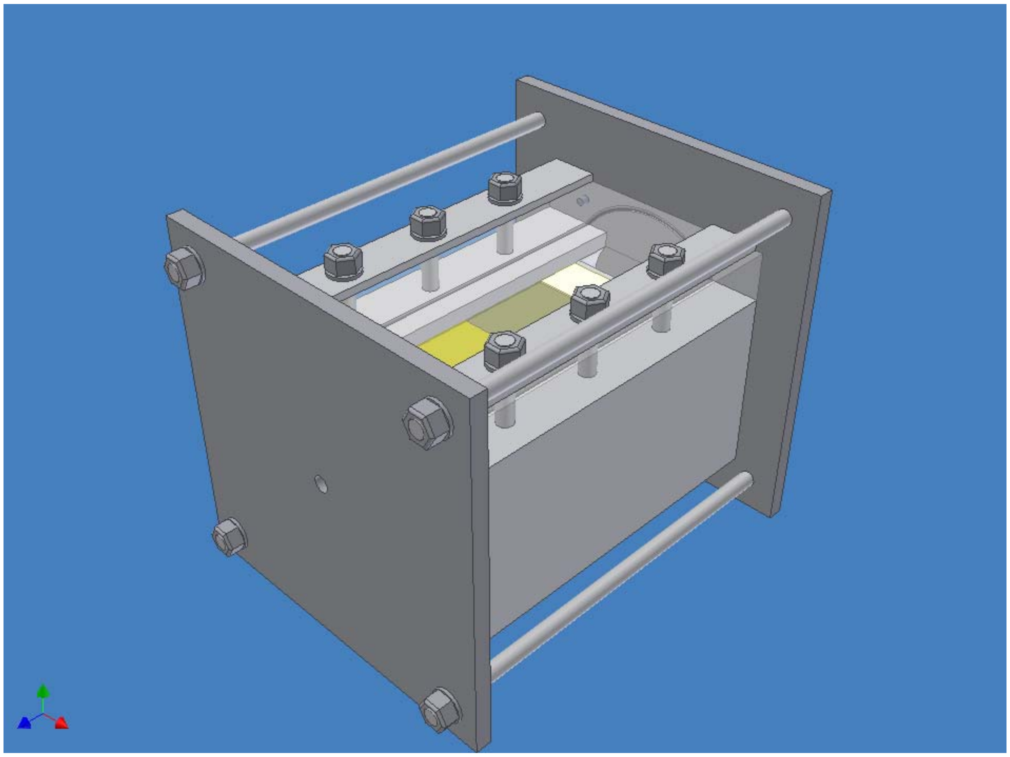


Figure 5.2 4-inch diameter filter test device

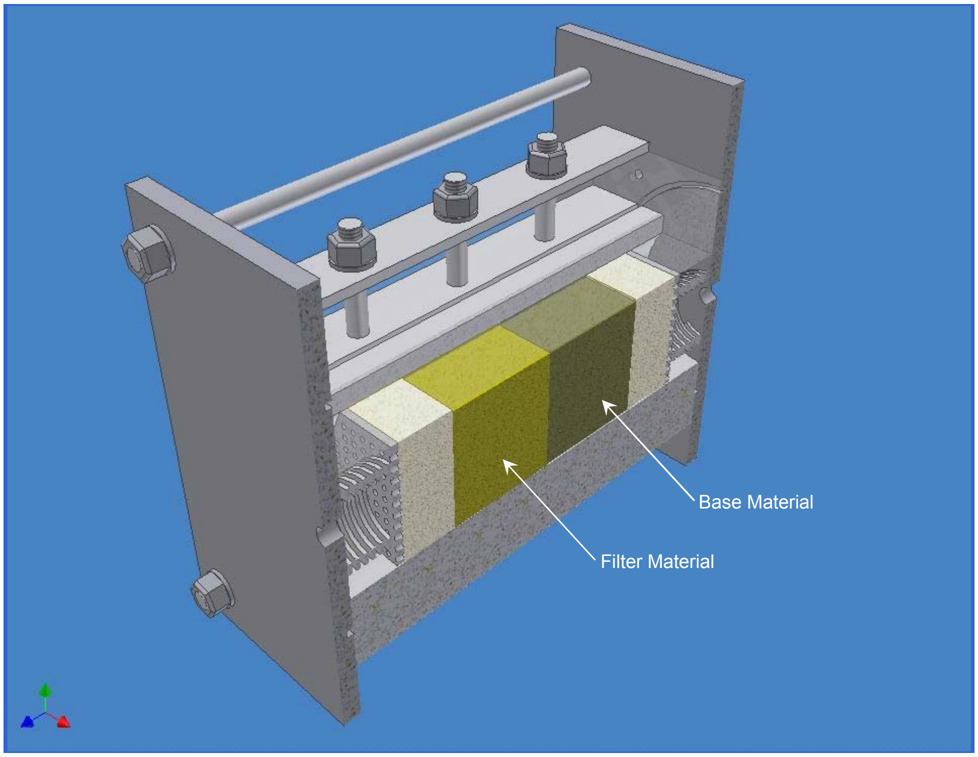


Figure 5.3 Longitudinal cross section through 4-inch diameter filter test device with compacted sample

5.3. Pilot Tests

5.3.1. Horizontal Crack Orientation and Horizontal Flow Direction

Tests 1 through 5 were conducted using the Teton Dam core material as the base material, and the Ochoco Dam filter material as the filter material. The Ochoco Dam filter material meets the USBR filter criteria for the Teton Dam core material.

In tests 1 and 2, the crack orientation was horizontal, and the flow direction was horizontal as shown in Figure 5.4. This condition is denoted here as HH. In this orientation, the filter material cannot close the crack by slumping, since gravitational forces tend to keep the crack open. Clogging is possible, however, as particle migration occurs due to flow of water through the specimen. Severe erosion was experienced in Test 1, and a continuous channel was eroded through the base and filter material. The effluent was visibly turbid throughout the test, and a stable condition was never reached.

Test 2 was conducted using the same conditions as Test 1, but the filter system successfully restrained the base material due to particle migration. Early in the test, particles of the base material covered the filter, and the filter and base then became "mixed." The mixed material was restrained by the pea gravel, as shown in Figure 5.5. The effluent was first turbid, and then quickly cleared as the test progressed.

These results showed that the HH condition, which does not permit slumping of the filter under the force of gravity, does not simulate the field conditions that are of interest for this study. Although testing with horizontal crack orientation offered some slight advantage with regard to test setup, it was decided that all subsequent tests should be performed with vertical crack orientations to better simulate field conditions.

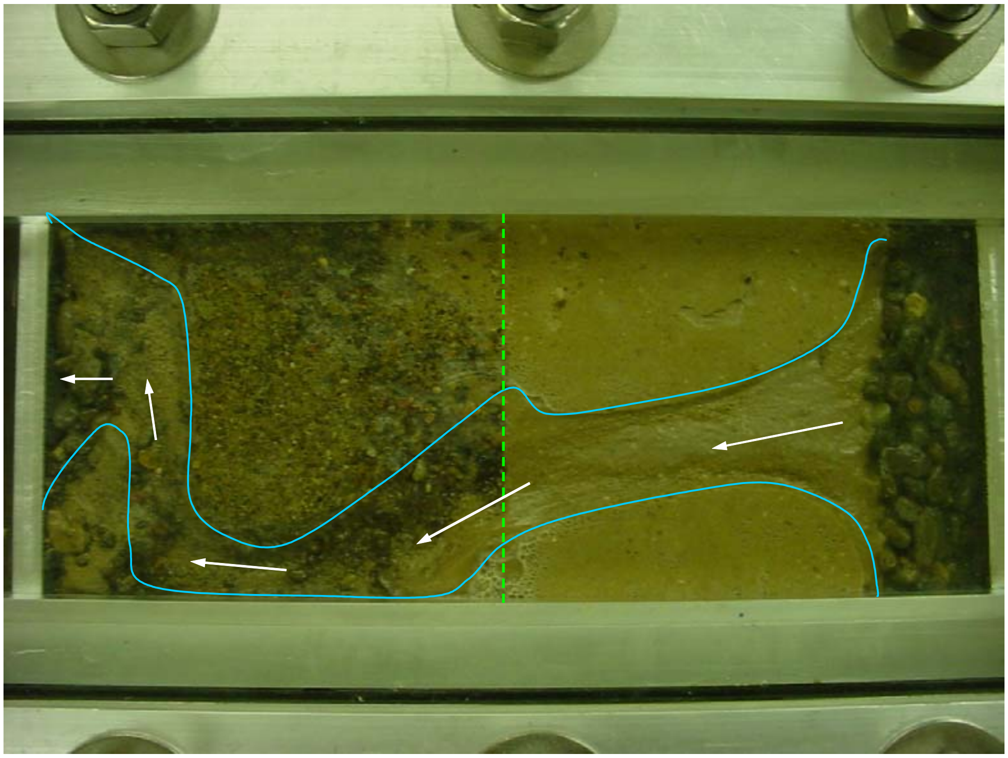


Figure 5.4 After Test 1 (HH condition)

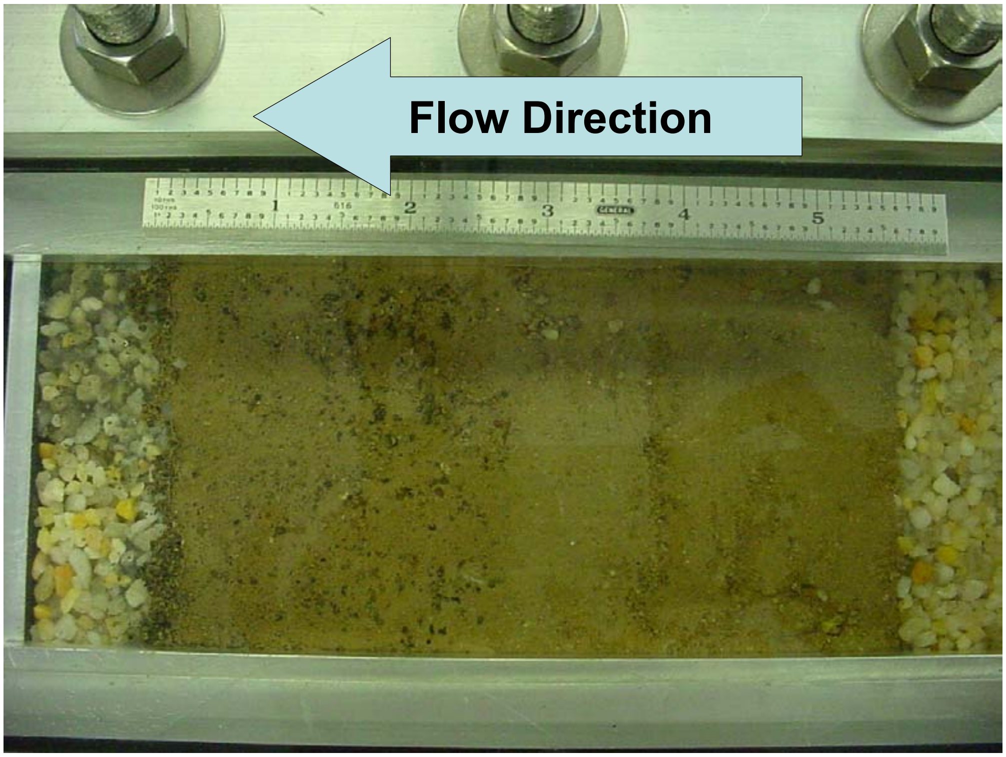


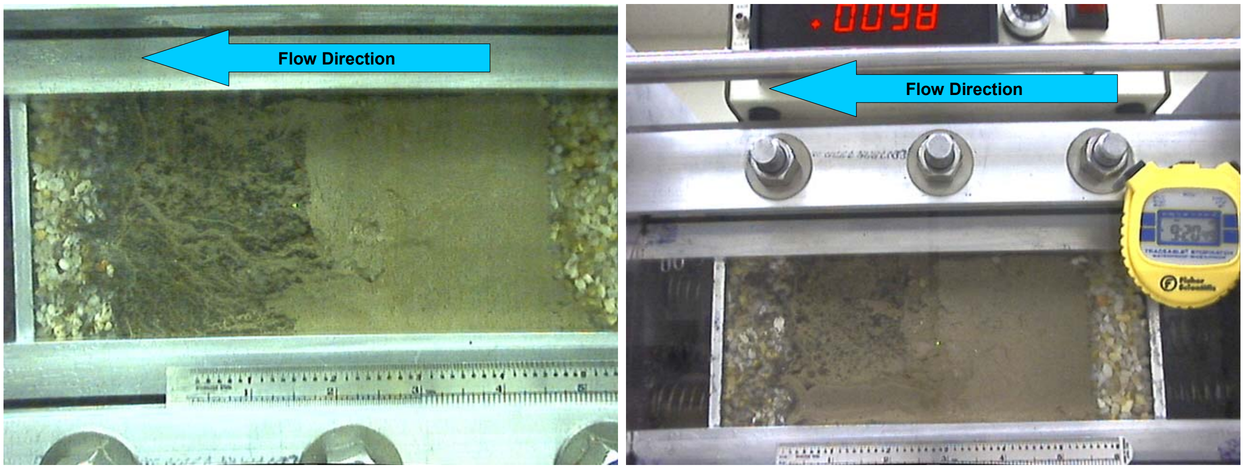
Figure 5.5 After Test 2 (HH condition)

5.3.2. Vertical Crack Orientation and Horizontal Flow Direction

Four tests (3, 4, 7, and 8) were performed with vertical crack orientation and horizontal flow, denoted here as condition VH.

Test 3 was performed using the Teton Dam core material and the Ochoco Dam filter material, with the filter test device rotated 90 degrees about its long axis, so that the plane of the crack was vertical. With flow in the horizontal direction, particles of the base material and the filter material migrated downstream and were restrained by the pea gravel as shown in Figure 5.6(a).

Test 4 (shown in Figure 5.6(b)) had the same conditions as Test 3, except that the section of the specimen comprised of base material was thicker, and a smaller hydraulic gradient was used. Although some base material was initially eroded, particles of the filter quickly migrated to collect on the pea gravel, and the effluent became clear.



(a) After Test 3 **(b) After Test 4**

Figure 5.6 Tests 3 and 4 (VH condition)

Test 7 used the Teton Dam core material as the base soil, and the filter material was fabricated from quartz sand so that D_{15F}/D_{85B} ratio was equal to 6. This represents a filter that is slightly coarser than allowed by the current USBR criteria. The specimen was compacted about 24 hours prior to testing. During the time between compaction and testing, the base material swelled and partially filled the crack, within the area outlined by the dashed red line in Figure 5.7. When flow was started, particles of the filter migrated downstream and were restrained by the pea gravel, and the filter then successfully restrained the base material.

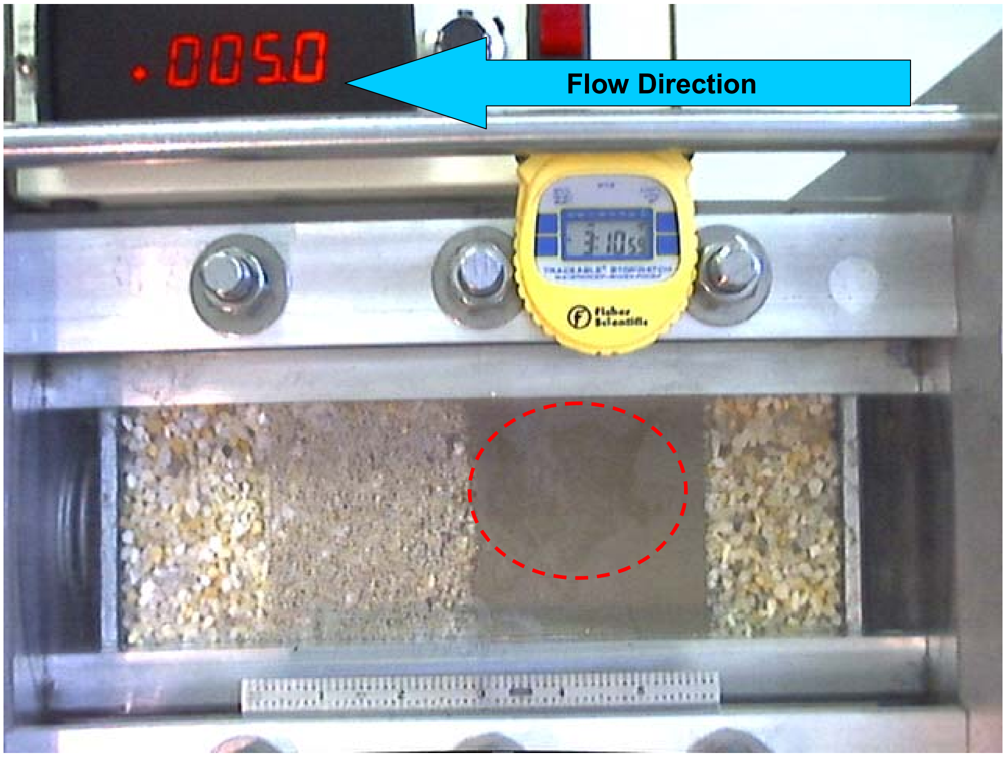


Figure 5.7 Before Test 7

Test 8 was conducted using the same conditions as Test 7, but the sample was tested soon after compaction. This test resulted in more base material being eroded, but the filter successfully restrained the base, as shown in Figure 5.8.

Test 7 and 8 were the first tests in which upstream pressures were measured. Figure 5.9 shows the variations of upstream water pressure with time measured in these tests. It may be seen that the pressures dropped as soon as the valve was opened, and increased as clogging developed. Even though the filter successfully restrained the base material, the pressure did not return to the original value, as may be seen in Figure 5.9. Close examination of the specimens during these tests, showed that empty spaces remained at the top of the crack, and that there was free flow through these empty spaces.

(a) After Test 7 **(b) After Test 8**

Figure 5.8 Tests 7 and 8 (VH condition)

Tests with vertical crack orientation and horizontal flow direction modeled the desired field condition, but it resulted in empty spaces at the top of sample the crack. Because dams have freeboard, such spaces in the field would most likely be above water, and therefore not involved in flow through the crack, even if the upper part of the crack remained open. Therefore the VH condition in the 4-inch filter test device imposes a more severe condition than would be expected in the field.

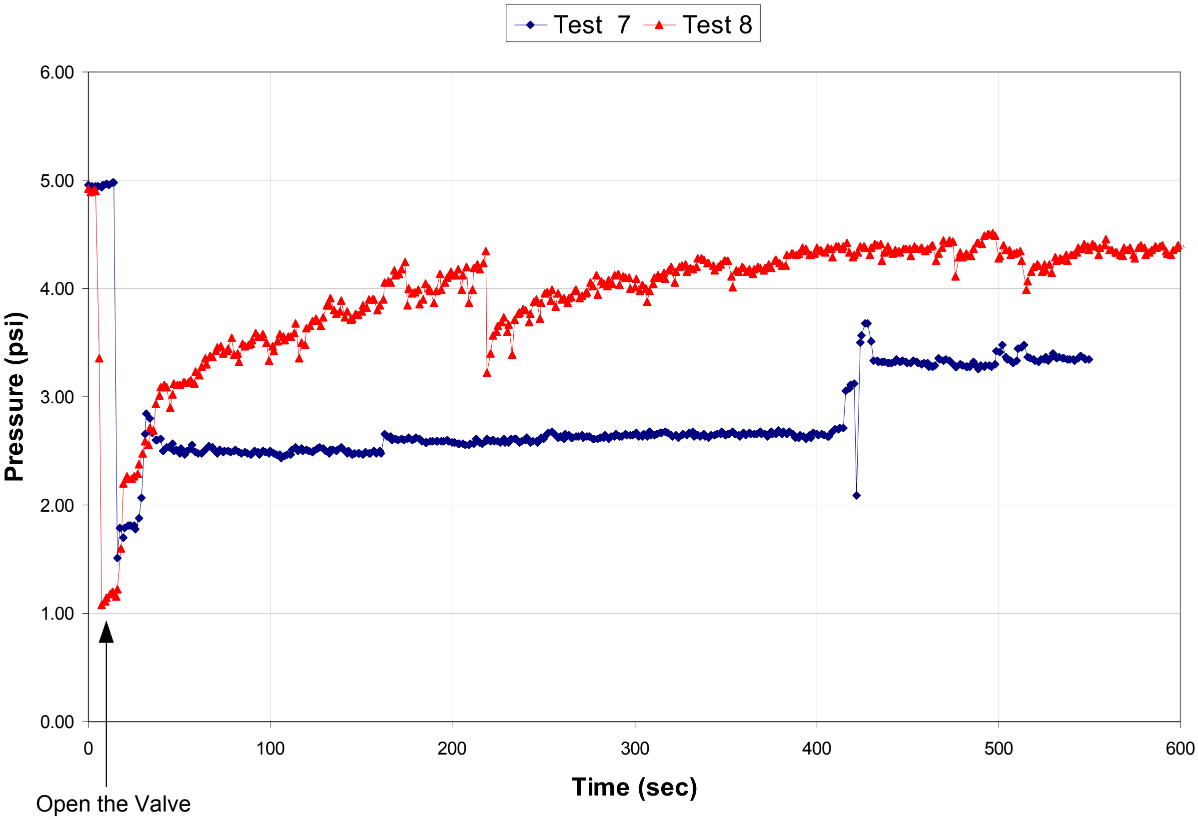


Figure 5.9 Pressure measurement of Test 7 and 8

5.3.3. Vertical Crack Orientation and Vertical Flow Direction

Tests 5 and 6 were conducted with the crack oriented vertically, and with the water flowing vertically downward through the crack. This condition is denoted here as VV.

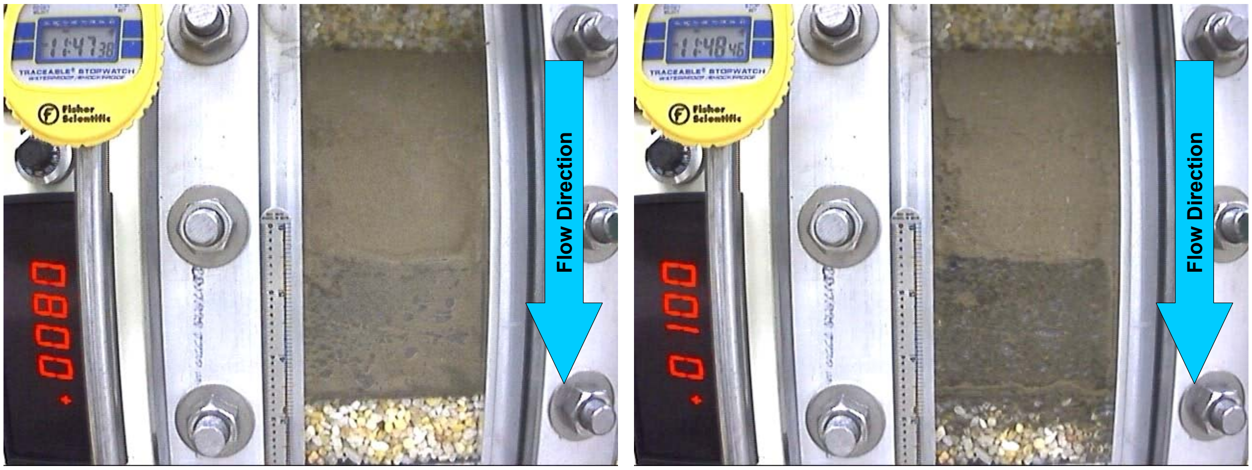
Test 5 was conducted before the data acquisition (DAQ) system was built, so no continuous record of pressure variation was made. Figure 5.10(a) shows Test 5 before opening the valve. On the top left, the digital clock shows elapsed time (the reading shown is 11 hours, 47 minutes, and 24 seconds), and the digital display at the left shows a voltage that represents the upstream pressure (0.0101 volts represent 5 psi pressure). As shown in Figure 5.10(b), the pressure immediately dropped by more than half (about 2 psi) after the valve was opened.

(a) Test 5 before opening the valve **(b) Test 5 immediately after opening the valve**

Figure 5.10 Early stage of Test 5 (VV condition)

As mentioned previously, the filter test device in this test (Test 5) was oriented vertically, with the base material above the filter material, and flow was downward. The average gradient used through the soil sample (i = 36) was slightly smaller than the values (i = 39 to 46) used in previous tests. During the test, the base material was first eroded and filled the crack, and then particles of the filter material also moved in to fill the crack, as shown in Figure 5.11(a). The effluent became clear very quickly. Figure 5.11(b) shows that the pressure returned almost to its initial value, and the filter material successfully restrained the base.

Figure 5.12 shows an enlarged view of Figure 5.11(b). It can be seen that a thin layer of the base material formed on top of the filter material that had slumped on top of the pea gravel. Subsequently, more filter material collapsed on top of the thin layer of base material. The condition shown in Figure 5.12 illustrates clogging mechanism described in Chapter 3, and shown by the sketch in Figure 3.5.



(a) Test 5 during the test **(b) Test 5 after the test**

Figure 5.11 Late stage of Test 5 (VV condition)

Figure 5.12 Clogging layer after Test 5

Test 6 was conducted to investigate whether the filter test device with vertical crack orientation was capable of showing filter failure for conditions under which filter failure should, in fact, occur. This test used pea gravel, which does not meet the USBR criteria for the Teton Dam core material, in place of the filter material. The ratio of the D_{15F} of the pea gravel divided by the D_{85B} of the Teton Dam core was equal to 25, far greater than the allowable value of five.

In this test, shown in Figure 5.13(b), most of the base material was washed through the pea gravel, and a stable condition was never reached. This result demonstrated that the successful performance of the filters in earlier were not an artifact of the test conditions, and were therefore indicative of the actual behavior of the filter materials tested.

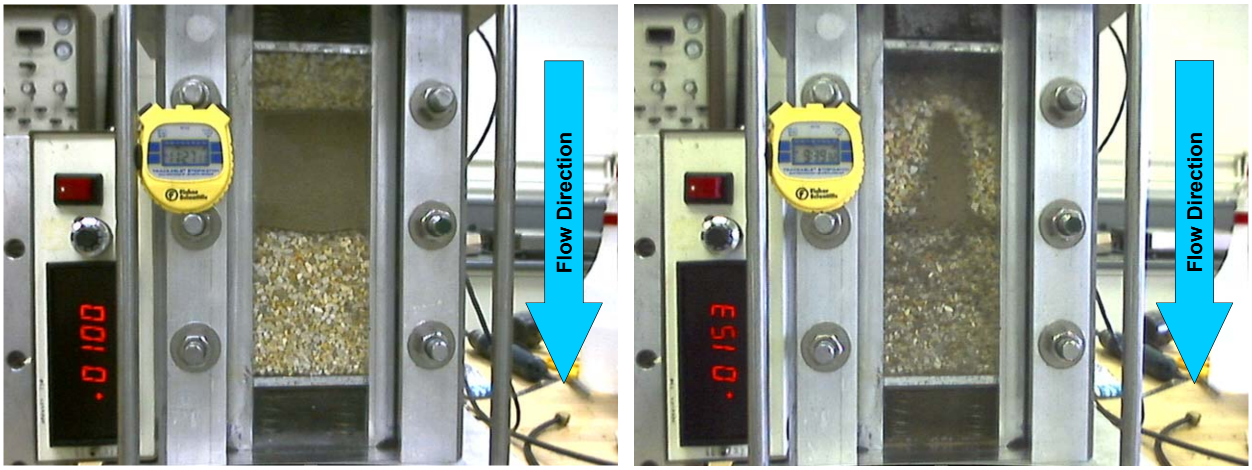
5.4. Compaction Procedure and Water Supply

In Tests 9 through 12, as in Test 1 through 8 described previously, the specimens were compacted using the standard Proctor compaction hammer, and using water pressures controlled by a water pressure regulator attached to the laboratory water supply line. Tests 9 through 12 showed that this method of compaction and this method of controlling water pressures were not adequate to achieve consistent results for all of the tests.

Tests 9 through 12 were performed to investigate the effect of fines content on filter behavior, one of the major objectives of the study. These tests showed, as did later tests, which filters with as much as 15% non-plastic fines were able to collapse, fill an initial crack, and satisfactorily retain the base material. However, the results of these tests were not systematic with regard to the effects of the percentage of fines on the variation of flow with time during the tests.

It was surmised that these erratic results were due to variations in the dry densities achieved with the standard Proctor hammer and energy: It was decided that for subsequent tests the specimens would be compacted using a moist tamping procedure, with careful control of the density of each lift. As explained subsequently, consistent results were achieved when this was done.

It was also observed during Tests 9 through 12 that the water pressures varied erratically during the tests, and it was evident that the water pressure regulator was not able to control the water pressures with sufficient uniformity. It was found that much more uniform water pressures could be achieved with a water supply tank using air pressures in the tank controlled by an air pressure regulator, and this system was used for all subsequent tests.



(a) Test 6 before opening the valve **(b) Test 6 after the test**

Figure 5.13 Test 6 (VV condition)

5.5. Major Test Results

5.5.1. Details for a Typical Test

As explained in previous sections, the apparatus and test procedures were developed as Test 1 through Test 12 were performed. Consequently, the procedures used for tests 9 through 12 were not standardized to the degree desired, and the results of these 12 tests are not reported in detail. Test 13 was the first in which the apparatus and test procedures were the same as used throughout the remainder of the tests.

The results of a typical test (Test 16) are shown in Figure 5.14, Figure 5.15, and Figure 5.16.

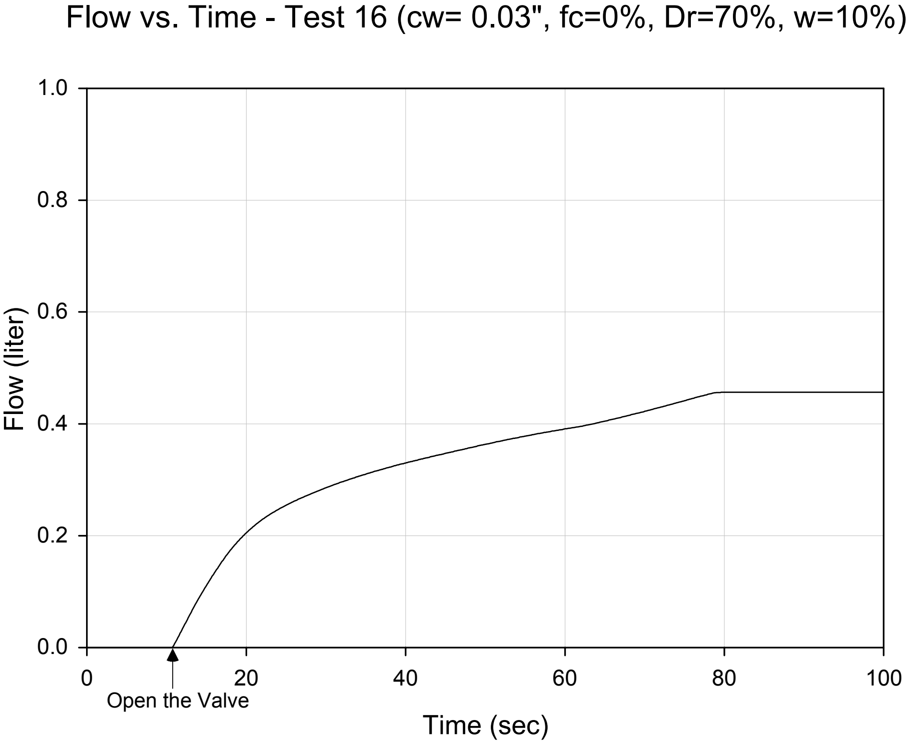


Figure 5.14 Flow vs. Time (Test 16)

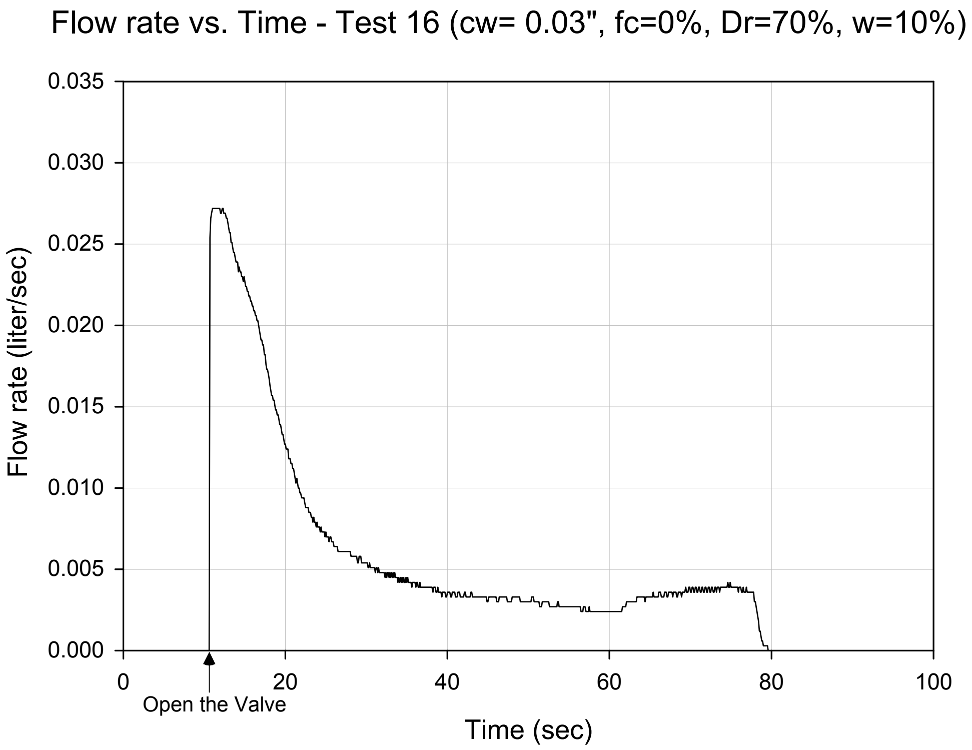


Figure 5.15 Flow Rate vs. Time (Test 16)

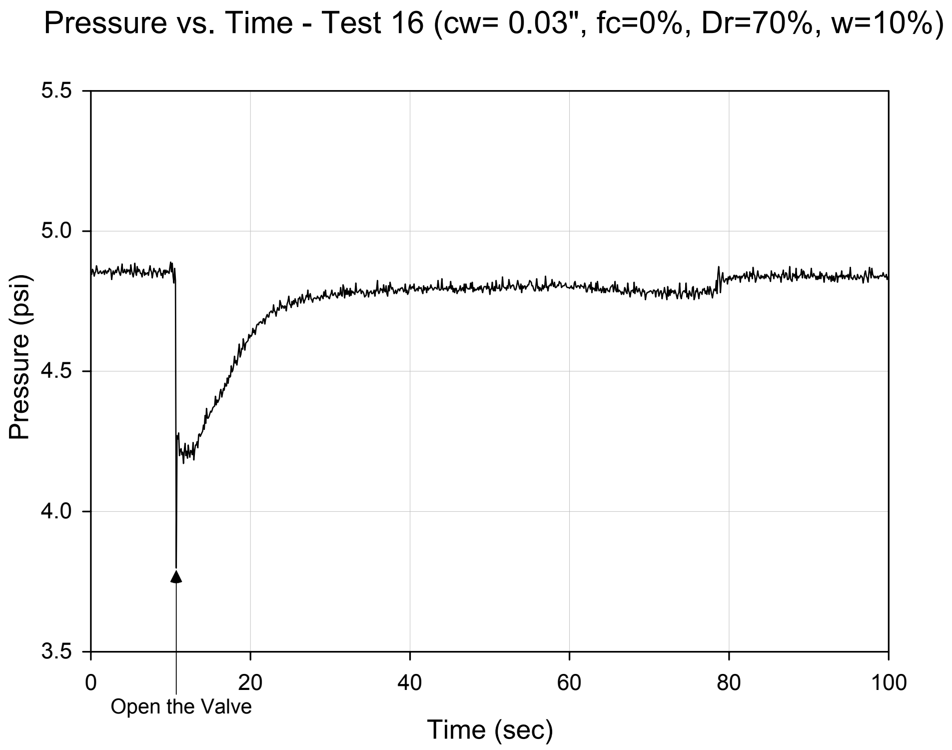


Figure 5.16 Pressure vs. Time (Test 16)

Figure 5.14 shows the variation of flow volume with time and Figure 5.15 shows the variation of flow rate with time. Flow through the test specimen began at t=10 seconds, when the flow control valve was opened. It can be seen that the flow rate was initially very rapid, and that it decreased essentially to zero in a period of about 80 seconds. At this stage in the test, the filter had collapsed and retained the eroding base material.

Figure 5.16 shows the recorded variation of pressure with time during the test. Immediately after opening the valve, the pressure dropped suddenly as the water flowed rapidly through the device. Within approximately 15 seconds the pressure had returned to near its initial value of about 4.7 psi.

It was found that the process of erosion and clogging during the tests often occurred episodically. As can be seen in Figure 5.15, there was evidence of a tendency for increased flow rate and subsequent rapid decrease in flow rate that is characteristic of these episodes of erosion, clogging and retention of the base materials by the filter. It is interesting to note, as can be seen in Figure 5.18, after the filter had reached an apparently stable condition there was a later episode of breakthrough and subsequent reestablishment of a stable condition in the period from about 350 to 400 seconds after the beginning of the test. The conditions remain stable throughout the remainder of the test, as can be seen in Figure 5.19. While the details of the tests vary somewhat from one test to the next, the characteristic behavior shown in Figure 5.14 through Figure 5.16 was consistent throughout Tests 13 through 27.

5.5.2. Effect of the Percent Fines

One of the primary objectives of this research program is to determine the effect of the fines content on the ability of a filter to collapse and fill a crack. Figure 5.17, 5.18, and Figure 5.19 show the results of Tests 16, 19, and 22. The only difference in the conditions for these tests was the percentage of fines in the filter material. In Test 16 the filter had no fines, in Test 19 the filter contained 5% fines and in Test 22 the filter contained 15% fines.

All three tests were conducted with an initial crack width of 0.03 inches, and with the filter compacted to a relative density of 70% at a water content of 10%. All three of these tests were successful, with the filter eventually collapsing and retaining the base material. After an initial reduction in pressure immediately after the valve was opened, the water pressures returned to their initial values very quickly, within about 20 seconds. It can be seen in Figure 5.17 that the flow rate diminished most quickly with the finest filter and most slowly with the coarsest filter.

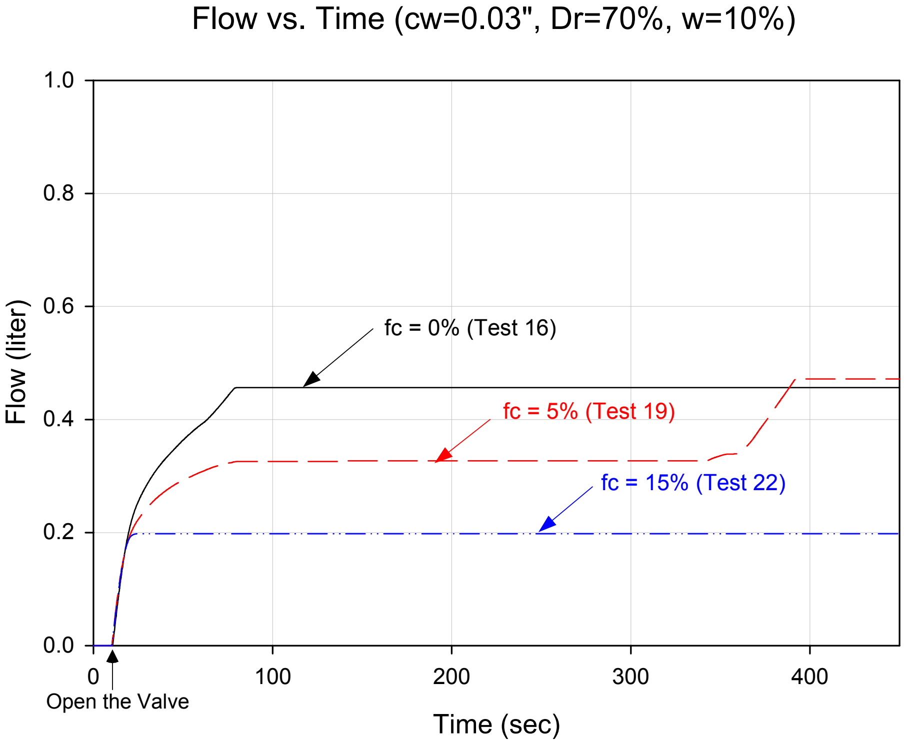


Figure 5.17 Flow vs. Time comparing Test 16, 19, and 22

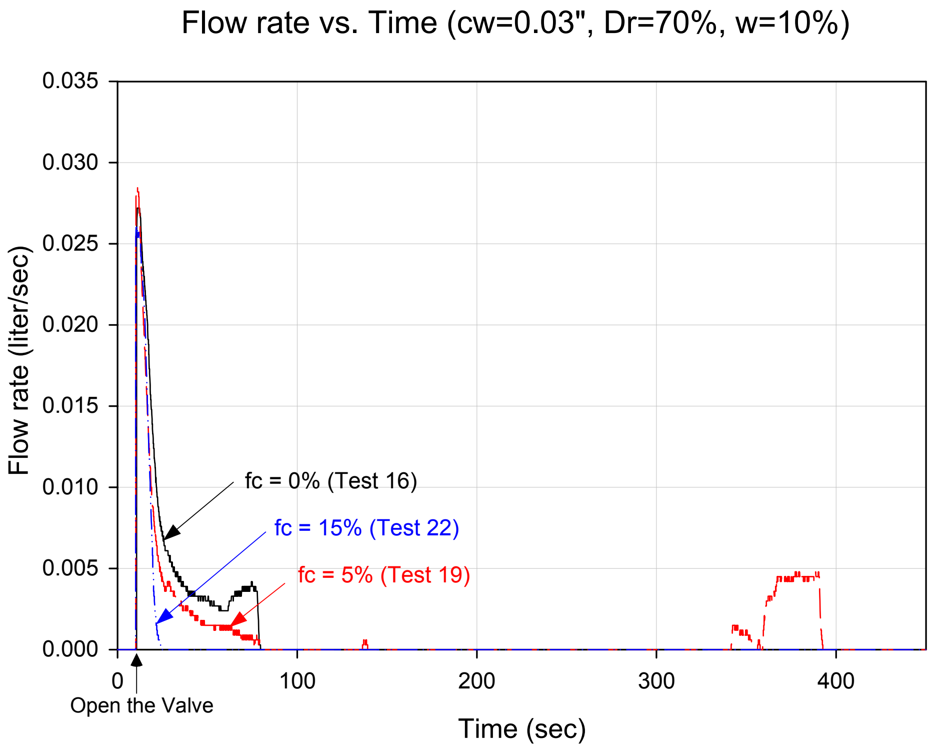


Figure 5.18 Flow Rate vs. Time comparing Test 16, 19, and 22

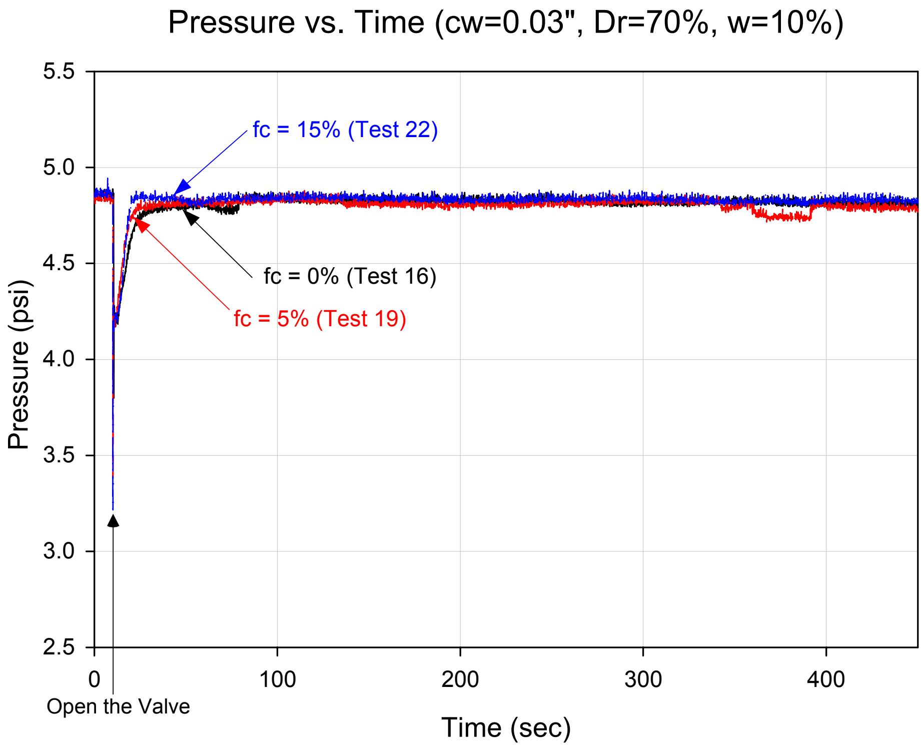


Figure 5.19 Pressure vs. Time comparing Test 16, 19, and 22

The conclusion based on the results of these three tests is that variation of the percentage of non-plastic fines from 0 to 15% does not change the ability of the filter to collapse, plug the crack, and prevent erosion of the base material.

5.5.3. Effect of Crack Width

It was considered important to investigate the width of the crack formed between the specimen and the wall of the filter test device, since this is an important boundary condition in the tests. The results shown in Figure 5.20, 5.21, and 5.22 indicate that variation of the crack width from 0.03 to 0.09 inches does not change the basic behavior of the specimens during the tests. Although there are some detailed differences in the test results, in all cases the filter was able to collapse and close the crack and retain the base soil, even with a crack width as large as 0.09 inches.

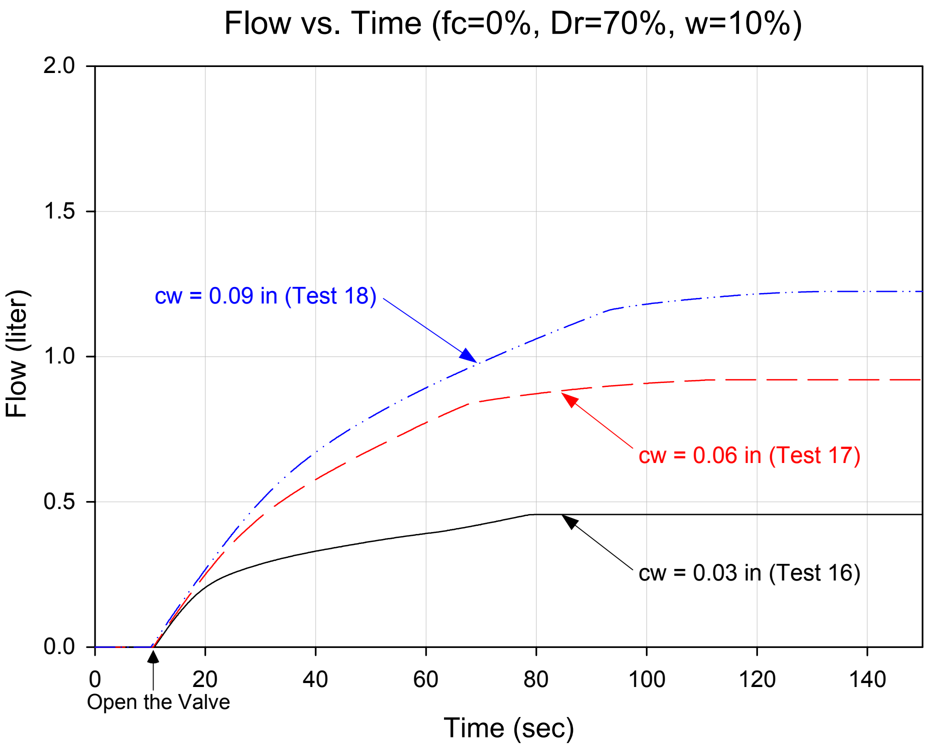


Figure 5.20 Flow vs. Time comparing Test 16, 17, and 18

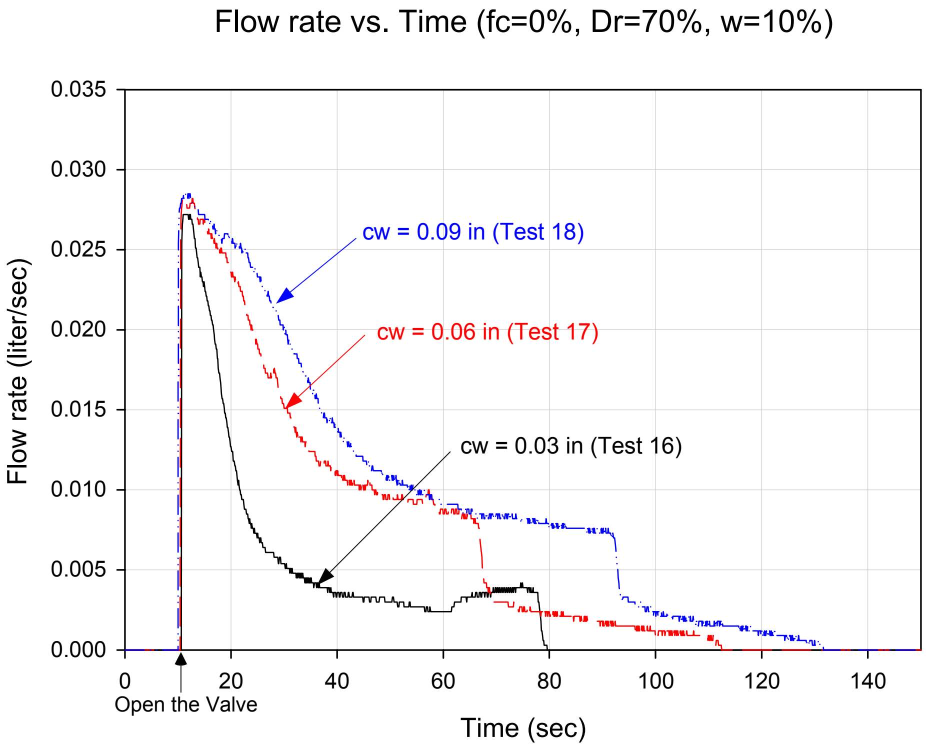


Figure 5.21 Flow Rate vs. Time comparing Test 16, 17, and 18

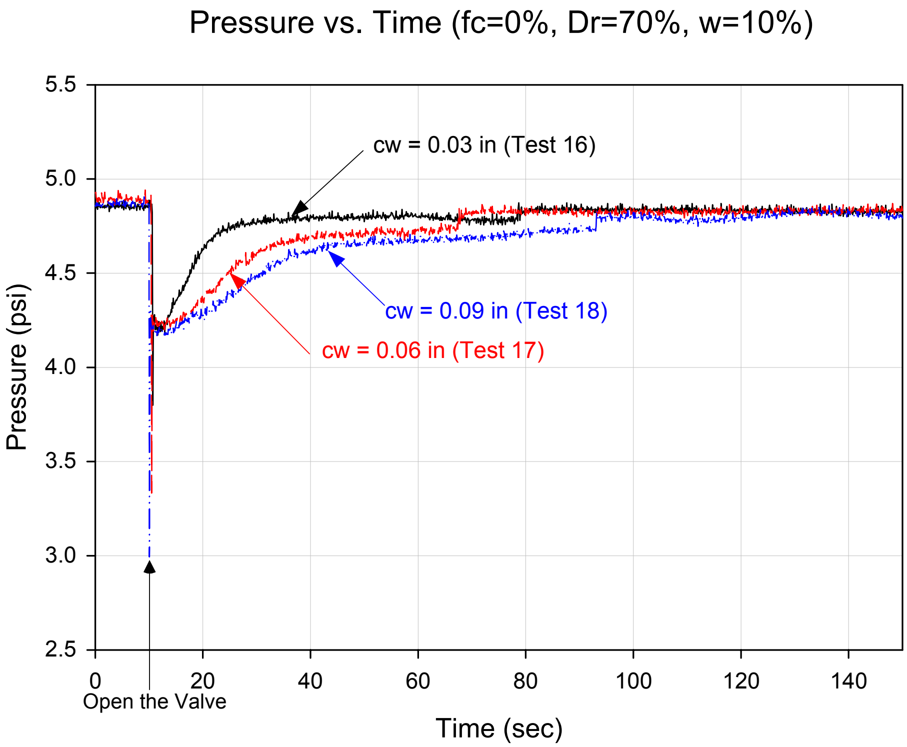


Figure 5.22 Pressure vs. Time comparing Test 16, 17, and 18

5.5.4. Effect of Density

The results of Test 13 and Test 16 are compared in Figure 5.23, 5.24, and 5.25. The relative density of the filter material in Test 13 was 50% and the relative density of the filter material in Test 16 was 70%. Although there are some differences in the rate at which the specimen reached a stable condition, both tests resulted in successful retention of the base by the filter. Test 13 is one of those in which there was a subsequent episode of collapse and reestablishment of a stable condition.

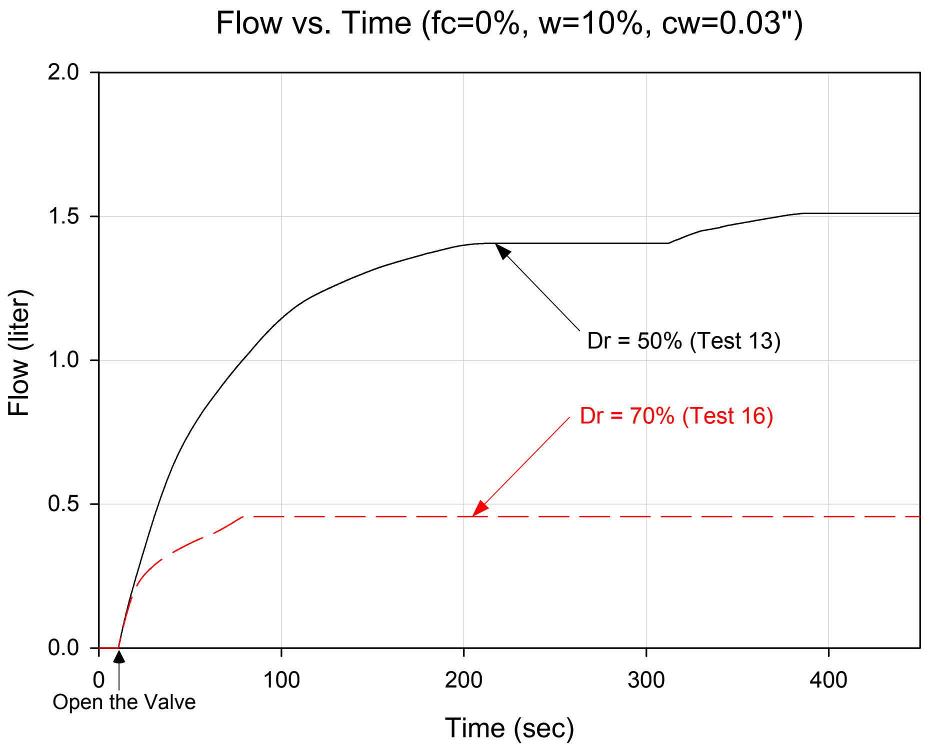


Figure 5.23 Flow vs. Time comparing Test 13 and 16

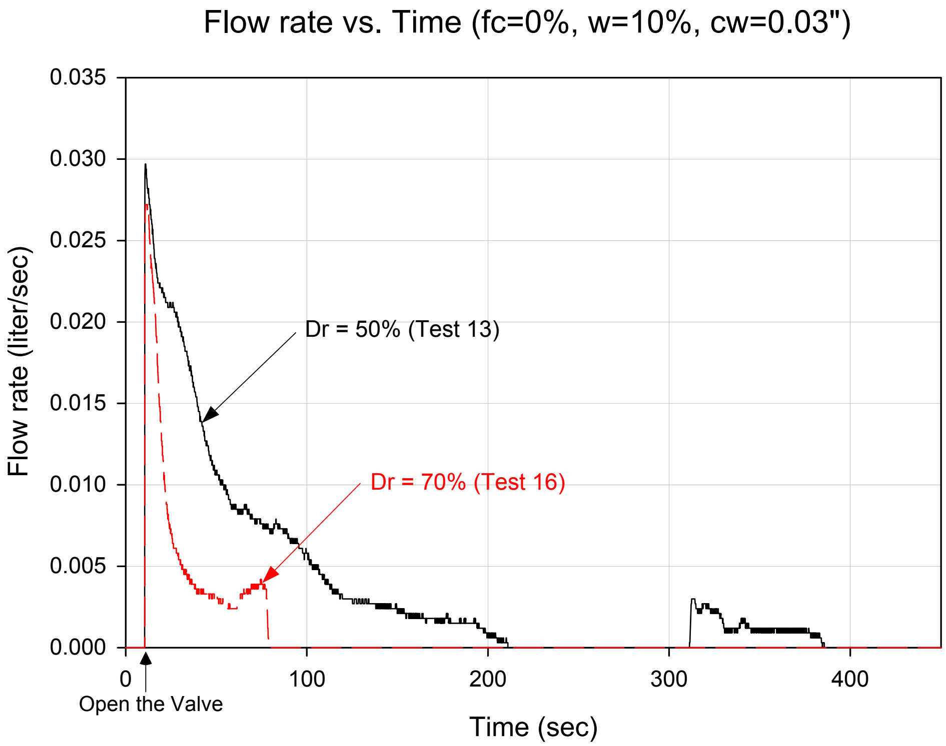


Figure 5.24 Flow Rate vs. Time comparing Test 13 and 16

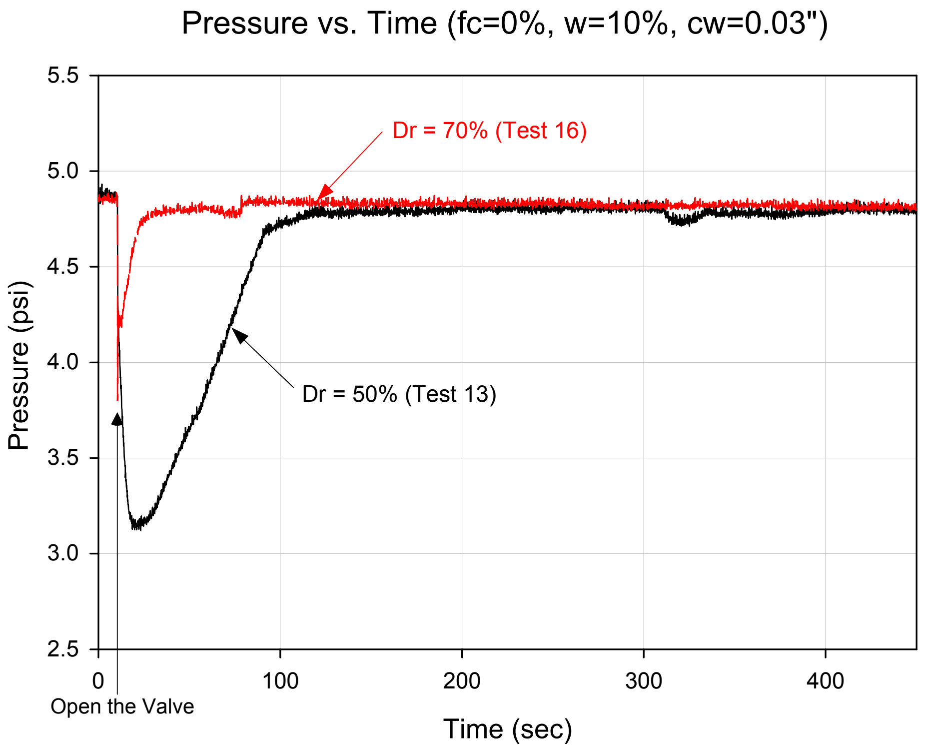


Figure 5.25 Pressure vs. Time comparing Test 13 and 16

5.5.5. Effect of Water Content

The effect of water content during compaction of the filter material can be seen by comparing the results of Test 16 and Test 25, which are plotted together in Figure 5.26, 5.27, and 5.28. These two tests had the same filter material, but different water contents. The results of these tests are nearly identical, with very similar flow rates versus time required to re-establish the initial pressure. This result might be expected, because the filter material is granular, and its compaction is not effected much by variation in compaction water content.

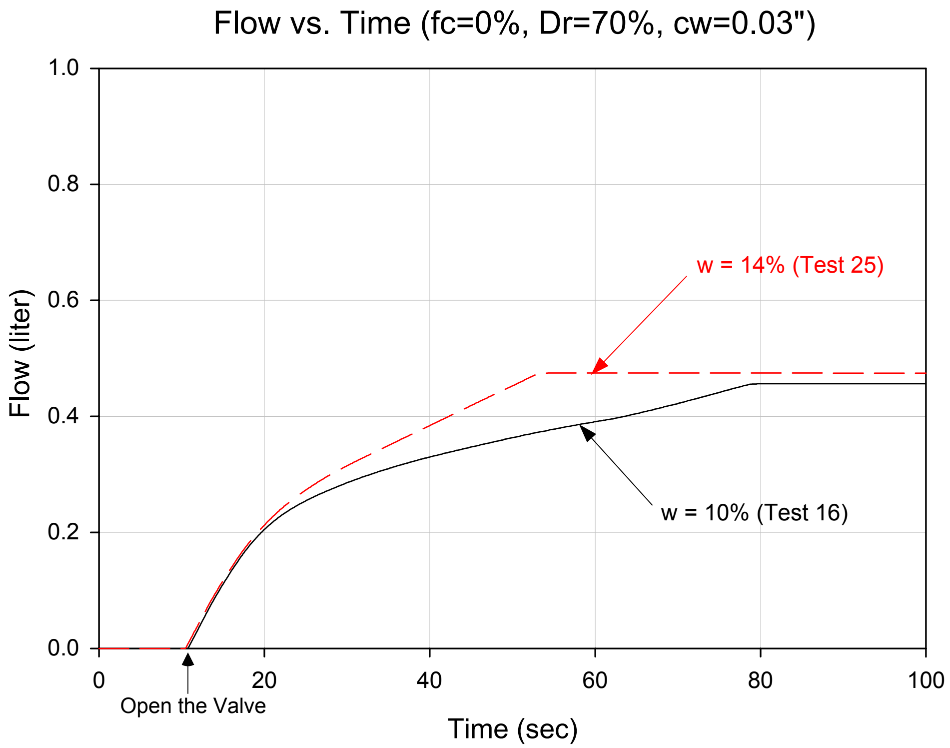


Figure 5.26 Flow vs. Time comparing Test 16 and 25

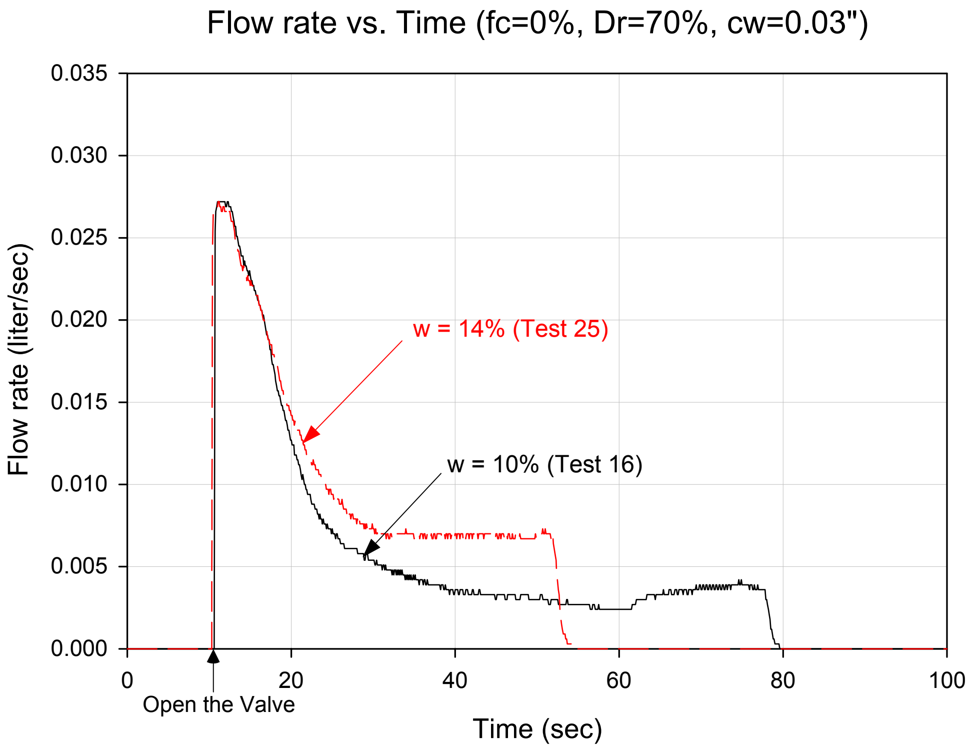


Figure 5.27 Flow Rate vs. Time comparing Test 16 and 25

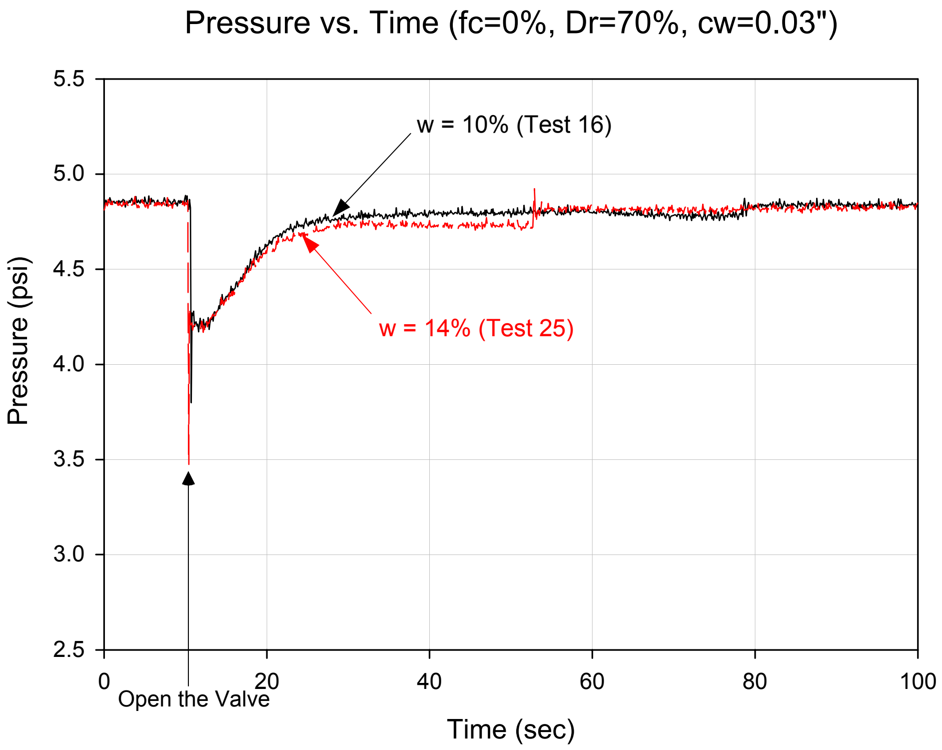


Figure 5.28 Pressure vs. Time comparing Test 16 and 25

Tests 24 and 26 were performed to determine if water content would have any effect on the behavior of filter materials containing fines. The results of these tests, conducted using filter material containing 15% fines, and compacted at water contents of 10% and 14%, are shown in Figure 5.29, 5.30, and 5.31. The results show that compaction water content did not have any significant effect on the results. Therefore, compaction water content does not appear to have any effect on the ability of the filter to collapse and block a crack, even if the filter material contains as much as 15% of non-plastic fine material.

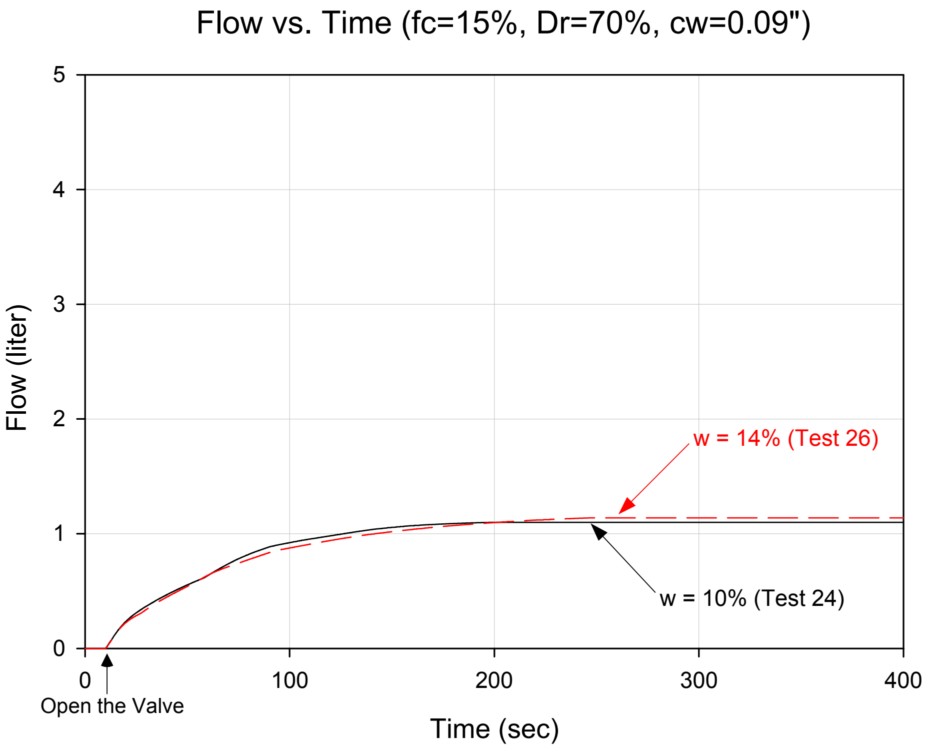


Figure 5.29 Flow vs. Time comparing Test 24 and 26

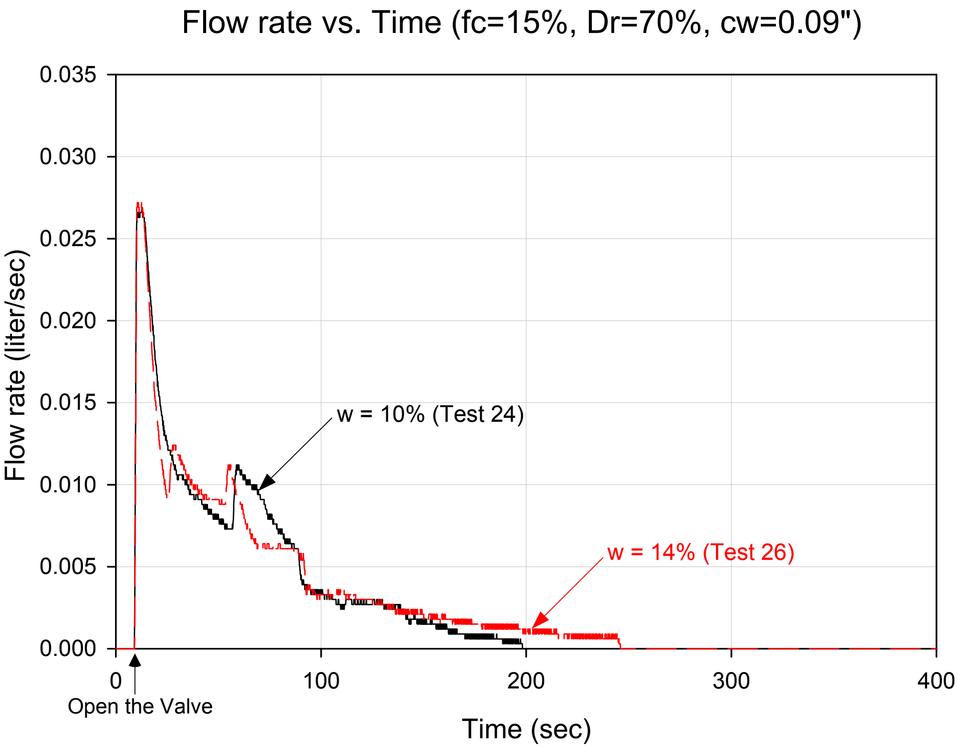


Figure 5.30 Flow Rate vs. Time comparing Test 24 and 26

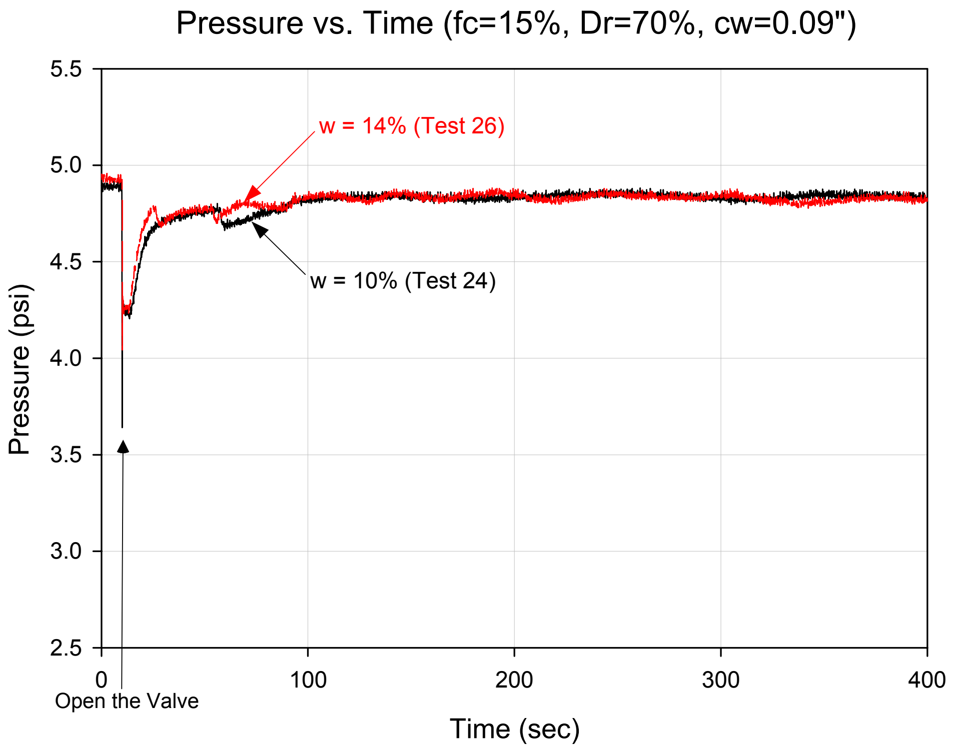


Figure 5.31 Pressure vs. Time comparing Test 24 and 26

5.6. Summary of Tests with 4-inch diameter Filter Test Device

The results obtained with the 4-inch diameter filter test device support these conclusions:

- An apparatus and test procedure has been developed that is capable of investigating the ability of filters to collapse and retain base materials that are initially cracked. The principal limitation is that the apparatus is only 4 inches in diameter, which only allows filter materials having maximum particle sizes of 0.25 inches.
- Tests have been performed to investigate the effects of the percentage of non-plastic fines in the filter (up to 15 percent), the effect of the crack widths (up to 0.09 inches), the effects of relative density in the range from 18% to 70%, and the effects of compaction water content in the filter ranging from 10% to 14 %. In all of the tests performed over

this range of variables the filter material successfully collapsed and retained the base material.

- The fact that the uniformly successful test results are not an artifact of the apparatus design is illustrated by the result of Test 6, in which the filter material was replaced by pea gravel too coarse to satisfy filter criteria. In this case, the base material was washed through the pea gravel continuously, and a stable condition was never reached during the test.
- A major finding of this research study is the fact that filters with as much as 15% of non-plastic fines are sufficiently cohesionless to collapse and retain the base material in an initially cracked specimen. Investigation of the effects of percent fines on the crack-stopping ability of filters was the major objective of this research.
- It should be noted that all of the filter materials used in these tests were composed of inert particles that exhibited no bonding or cementation during compaction. Bonding or cementation during compaction would be expected to have a major effect on the ability of filters to perform as crack stoppers.