A STUDY OF ROTARY JETS FOR MATERIAL REMOVAL

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ABSTRACT

Rotating waterjets have revolutionized the waterblast cleaning industry. Their capability and efficiency have greatly enhanced the use of waterjet technology. Over the last 15 years a large number of swivels and spinning nozzles have been developed. As a result, a wide variety of tools are available, with very different operating characteristics. Some of the differences are the result of optimizing the tool for different types of work.

This paper presents the results of testing to determine the influence of different operating parameters on jet performance and effectiveness. The parameters studied included: pressure, rotation speed, standoff, size of jets, angle of jets, and type of target material. Operating pressures of 35 to 140 MPa (5,000 to 20,000 psi) and flow rates of 15 to 170 lpm (4 to 45 gpm) were used.

The two target materials tested, concrete and rubber, have very different jetting characteristics. The concrete with small aggregate is hard and brittle. It erodes as grains and spalls in larger pieces. The neoprene rubber is pliable and very uniform without any fissures or boundaries of weakness. It requires the jet to cut and slice each piece removed.

Depth of cut and volume removed were the primary results measured and analyzed, while visual and subjective observations are included.

1. INTRODUCTION

Rotating waterjet nozzles allow large surface areas to be covered quickly. High rotation speeds allow the jets to hit the surface multiple times, creating a high speed erosion process. The purpose of the research conducted for this paper was to determine the effectiveness of various rotation speeds in two materials with widely differing jetting characteristics, as well as the effect of rotation speed on jet quality, as pressures, flow rates and standoffs were varied.

The concrete and rubber chosen for the testing are representative of two very different material types that waterjets can remove. In the concrete, the jets act to erode the cement which binds the harder aggregate together and also pressurize microjoints and cracks in the concrete. Because the concrete is brittle, large pieces are broken and spalled off by the jet action. This is the typical effect of waterjetting on materials with a grainy structure. The rubber is more homogeneous and pliable. While the jets can cut and erode this material, each piece removed must be completely cut free by the jet, as any ribs left between jet passes will remain attached.

The pressures, flow rates, standoff distances and rotation speeds selected for these tests are representative of realistic, full scale conditions. The jet path diameters chosen are small compared to what is typically used for surface cleaning, but considered valid for material removal and predicting larger diameter performance.

2. TEST PROCEDURE

The test samples of concrete and rubber were placed on a stand providing fixed standoffs. A high pressure water swivel was fitted with nozzle arms and jets, and rotation was provided by an air motor and belt drive. The rotating head traversed along a rail, chain driven and powered by an electric motor, at a fixed traverse rate of 3.3 m/min (11 ft/min). This arrangement is shown in Figure 1.

The concrete test samples consisted of 30 cm (12 in.) square x 5 cm (2 in.) thick blocks, with 1 cm (3/8 in.) minus aggregate in a 3000 psi mix. The rubber test samples were 18 cm (7.3 in.) square by 5 cm thick, 60 durometer neoprene. A photo of each after testing is shown in Figure 2.

For the concrete cutting tests, the nozzle arms were fixed at a 90° angle to the concrete surface. Two diameters of jet path were tested, 13 cm (5 in.) diameter and 22 cm (8.6 in.) diameter. Configurations of 2 and 4 jets were also compared. Standoff distances were tested at 2.5, 11.5, and 25.4 cm (1, 4.5 and 10 in.). Rotation speeds of 125 to 3000 rpm were evaluated.

The rubber cutting tests were conducted with 2 jets in a 13 cm (5 in.) diameter jet path. Jet angles were varied from 45° to 90°, at a fixed vertical standoff distance of 15 cm (6 in.). Rotation speeds of 250 to 3000 rpm were evaluated.

In both materials, pressures and flows were selected to allow equivalent power output thru the jets. The concrete cutting was tested at water pressures of 35, 70, 100 and 140 MPa, (5,000, 10,000, 15,000, and 20,000 psi) while the rubber cutting was tested at pressures of 70, 100 and 140 MPa (10,000, 15,000, and 20,000 psi). Nozzle diameters from .5 to 2.8 mm (.021 to .109 in.) were selected to result in power outputs of 33.6 and 93.2 kW (45 and 125 hp). Round tapered carbide nozzles 1.5 cm (.6 in.) long with a Cd of .9 and vane flow straighteners were used for all tests. Earlier testing had confirmed that this nozzle design was equal or superior to any commercially available nozzle.

Upon completion of each test, the blocks were measured to determine the maximum depth of cut and the volume removed. The rubber blocks were weighed before and after the cutting pass to determine the volume removed. The struck sand method was used to determine the volume removed from the concrete blocks. This method of measurement involved the filling of the removed area on the block with fine sand and then weighing this volume of sand and converting the weight to a volume. A total of 42 tests were conducted in rubber and 204 in the concrete. The data was broken down using a factorial analysis, where at each condition to be studied an average was taken of the data points relating to the analysis.

3. RESULTS

3.1 Concrete Material Removal

3.1.1 Effect of Pressure

The effect of increasing pressure on efficiency of concrete removal is shown in Figure 3. While a pressure of 35 MPa (5,000 psi) could begin to remove small amounts of the cement, an increase in power by increasing the flow rate had little effect. The jets did not penetrate the cement enough to allow the aggregate to be broken free, which blocked further erosion of the cement binder. The energy required at 70 and 100 MPa (10,000 and 15,000 psi) is less than at 140 MPa (20,000 psi), which demonstrates that once a pressure above the threshold for the material is reached, it is more effective to apply power through increased flow rate than through increased pressure for maximum volume removal. The critical pressure at which this occurs is dependent on the material, as is demonstrated by a comparison to the rubber removal results.

3.1.2 Effect of Rotation Speed

The analysis of volume removed versus rotation speed at pressures of 70 MPa (10,000 psi) and above is shown in Figure 4. These are values averaged for the three standoff positions, as well as the three pressures.

For the two jet power curves shown in the graph, the rotation speed for the most effective material removal was between 500 and 2000 rpm. At the diameter the jets were rotating in, the linear nozzle speed was between 3.4 m/sec and 13.4 m/sec (11 and 44 ft/sec) respectively. In this speed range, the efficiency was twice that at 125 rpm, and 45 percent better than that at 3000 rpm.

When the rotation speed was increased to 3000 rpm (66 ft/sec) the overall effectiveness of the jets was decreased. This appeared to be due to the degredation of the jet as it moved through the air at higher rotation speeds. This is especially true for smaller jet sizes. The specific energy of the lower power curve with smaller jet diameters increases at a much greater rate than that at the higher power, which has larger jet diameters.

The poor efficiency at 125 rpm was partially due to the ribs of material left between jet passes, as illustrated in Figure 5. Another contributing factor to the lower efficiency of volume removal at the slower speed was due to the decreased depth of cut. Normally one would suppose that a slower speed would allow a deeper depth of cut; however, in rotary material removal the higher rotation speed with successive passes of the jets permits the harder and unjettable aggregate to be removed, allowing the jets to penetrate deeper by removing the easily eroded cement binder. A comparison of the maximum depth of cut to the rotation speed, illustrated in Figure 6, shows that the maximum depth of cut occurs at a rotation speed of around 1000 rpm, which corresponds with the maximum volume removal. The maximum depth of cut at 125 rpm was less than the maximum depth of cut at higher speeds, showing that the jets were more effective in this material in making multiple high speed shallow passes rather than single slow cuts.

3.1.3 Effect of Standoff and Rotation Speed

An analysis of the specific energy for material removal at standoff distances of 2.5, 11.4 and 25 cm (1, 4.5, and 10 in.) shows the degradation of the jets due to high rotation speed, as illustrated in Figure 7. The jet performance decreased by approximately 50 percent over this standoff range at speeds of 500 to 2000 rpm, while at 3000 rpm the jet performance decreased by 70 percent over the standoff range.

The volume removed as a function of standoff distance was also plotted relative to jet power at standoffs of 2.5 and 25 cm (1 and 10 in.) (Figure 8). For 34 kW (45 hp) at 500 to 2000 rpm the specific energy increased by a factor of 2.5 at the 25 cm (10 in.) standoff, but at 3000 rpm the specific energy increased by 4.5 times at the 25 cm (10 in.) standoff. At 93 kW (125 hp), the specific energy was doubled from 500 to 2000 rpm, and increased by 2.5 times at 3000 rpm over the standoff range of 2.5 to 25 cm (1 to 10 in.) This shows that jets from smaller nozzle orifice sizes are more susceptible to degredation from higher rotation speeds, just as they are to increased standoff distance.

3.1.4 Effect of Four Jets Compared to Two Jets

These tests divided the flow used previously in two larger jets into four smaller jets of equivalent flow. When efficiency of material removal was compared, the effect was nearly the same between 500 and 1000 rpm, but when the rotation speed was increased to 2000 rpm, the four jet combination had a reduced efficiency of 20 percent. Refer to Figure 9. This decrease was due to the smaller nozzle orifice size, which allowed the jets to be degraded at the higher rotation speed. The advantage to the use of four jets as opposed to two jets would be in surface preparation, where four jets would reduce the amount of streaking between jet paths at the same rotation speed as two jets, if the standoff distance was kept to a minimum.

3.1.5 Effect of Increased Jet Path Diameter

In this series of tests, the jet path diameter was increased by 72 percent, from 13 to 22 cm (5 to 8.6 in.). At the larger jet path diameter, the linear velocity of the jets ranged from 5.8 m/sec (19 ft/sec) at 500 rpm to 23 m/sec (75 ft/sec) at 2000 rpm. With the larger jet path diameter the maximum depth of cut was decreased by 20 percent, but the larger area covered allowed the volume removed to increase. The effect on specific energy at 93 kW (125 hp), shown in Figure 10, was an increased efficiency of 25 percent over the smaller diameter jet path effect at a rotation speed of 500 rpm, but at a rotation speed of 2000 rpm, the specific energy of material removal by the 22 cm (8.6 in.) diameter was only 10 percent less than that of the 13 cm (5 in.) diameter path.

At 34 kW (45 hp), the specific energy of the 22 cm (8.6 in.) diameter jet path was twice that of the 13 cm (5 in.) diameter jet path at all rotation speeds. Again this was due to the higher linear speed of the jets created by the larger diameter, and the degrading effect of this speed on the smaller jet orifice size.

3.2 Rubber Material Removal

3.2.1 Effect of Pressure and Flow Rate

The effect of increasing pressure on efficiency of material removal in the rubber is shown in Figure 11. In this material the specific energy was decreasing as the pressure reached 140 MPa (20,000 psi), although between 100 and 140 MPa (15,000 and 20,000 psi) the curve has leveled, indicating that the optimum pressure for removal of this material has almost been reached.

3.2.2 Effect of Rotation Speed

In this series of tests, the angle of the jets was perpendicular to the surface, and only rotation speed was directly compared. At 250 rpm, the depth of penetration into the material was 25 percent deeper than at 1000 rpm, and 40 percent deeper than at 3000 rpm, as shown in Figure 12. This is in contrast to what occured in the concrete, where the slower speeds did not cut as deeply as the higher rotation speeds allowed. However, as in the concrete, the maximum volume of rubber removed occurred at the higher rotation speeds, due to the ribs of material between slow speed deep cuts not being removed. At 1000 and 3000 rpm, the material was removed as a fine powder, with little evidence of jet path on the remaining material. The graph in Figure 13 compares the specific energy for material removal at 34 and 93 kW (45 and 125 hp) as a function of rotation speed. It can be seen that at the lower power the specific energy was lower at slower rotation speeds, while at the higher power 3000 rpm was more effective, although the curve has leveled off at this speed.

3.2.3 Effect of Jet Angle

For the rubber to be removed it requires that the jet completely cut pieces loose from the block. The jet angle therefore can be important to the removal process. In this series of tests an attempt was made to take advantage of the combination of greater depth of cut at slower speeds with the jets angled to the surface to remove as strips the ribs of material left between cuts.

Angles of 90, 75, 60 and 45 degrees were compared; these combinations are shown in Figure 14. The result of this series of tests is shown in the graph of Figure 15. The greatest effect occurred at 250 rpm, where the specific energy at 60 degrees was 36 percent less than the energy required at 90 degrees. At 1000 rpm, the greatest improvement in efficiency also occurred at an angle of 60 degrees, where the specific energy was 34 percent less than at the 90 degree angle.

At 250 rpm, the rubber was removed as crescent shaped pieces up to 3.3 cubic centimeters (0.2 cu in.) in volume. At 1000 rpm, the rubber was again removed as tiny chips. These two types of pieces are shown in Figure 16.

4. CONCLUSIONS

4.1 Effect of Pressure and Flow

In the two types of materials tested for this research, it was demonstrated that a selected material has a threshold jet pressure below which the material will not be affected by the jet, and an optimum material removal pressure above which an increase in power through increased pressure will have diminishing returns. When this point is reached the best way to increase material removal is to increase the power by increasing the flow rate.

4.2 Effect of Rotation Speed

Based upon the results of this preliminary study, an optimum jet tip speed range for removal of concrete was found to be between 6 and 15 m/sec (20 and 50 ft/sec). A degredation of jet quality occurred with jet tip speeds above 15 m/sec (50 ft/sec) in the power range of 34 to 93 kW (45 to 125 hp). For the rubber material removal with jets perpendicular to the surface, a jet tip speed less than 3 m/sec (10 ft/sec) was more effective in the 34 kW (45 hp) range, while speeds up to 18 m/sec (60 ft/sec) were more effective in the 93 kW (125 hp) range. Therefore, smaller jets need slower rotation speeds to maintain jet effectiveness.

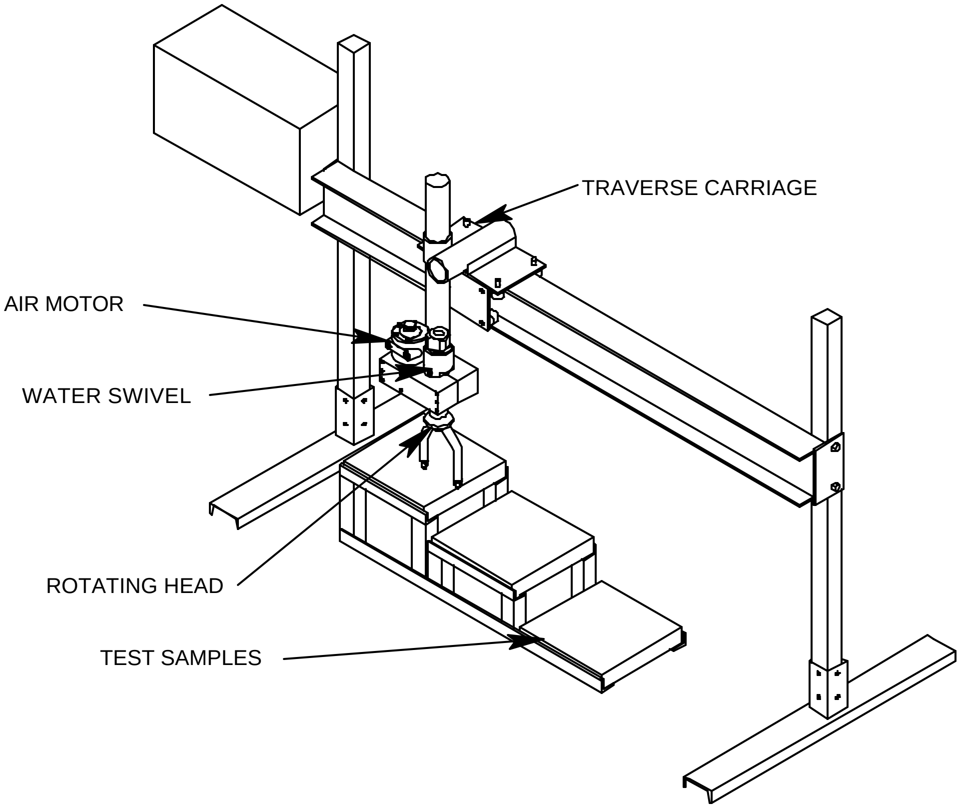
If these speeds were to be extrapolated to a surface cleaner with a 60 cm (24 in.) diameter jet path, the optimum rotation speed range for maximum volume removal would range from 200 to 500 rpm. Above this rotation speed jet degradation would begin to occur, reducing jet effectiveness. However, if one wanted to evenly remove only a thin layer of material or softer coating, rotation speeds greater than 500 rpm would be desirable.

If surface removal without streaking is desired, the number of jets can be increased while maintaining the same flow as with the smaller number of jets. There was no effect on performance changing from 2 jets to 4 jets of equivalent flow at jet tip speeds below 7.5 m/sec (25 ft/sec), but above this speed degredation of the jets begins to occur and at 15 m/sec (50 ft/sec) the performance is reduced by 25 percent.

It is important to keep the standoff distance as small as possible at higher rotation speeds; a change in standoff distance from 2.5 to 10 cm (1 to 4 in.) at 3 m/sec (10 ft/sec) reduced the effectiveness by 40 percent, while at 15 m/sec (50 ft/sec) the effectiveness was reduced by 55 percent. Other factors to be considered when selecting a rotation speed for operation are the increased wear and vibration with increasing speed on the rotating components and seals being used in the equipment.

4.3 Effect of Varying Jet Angle

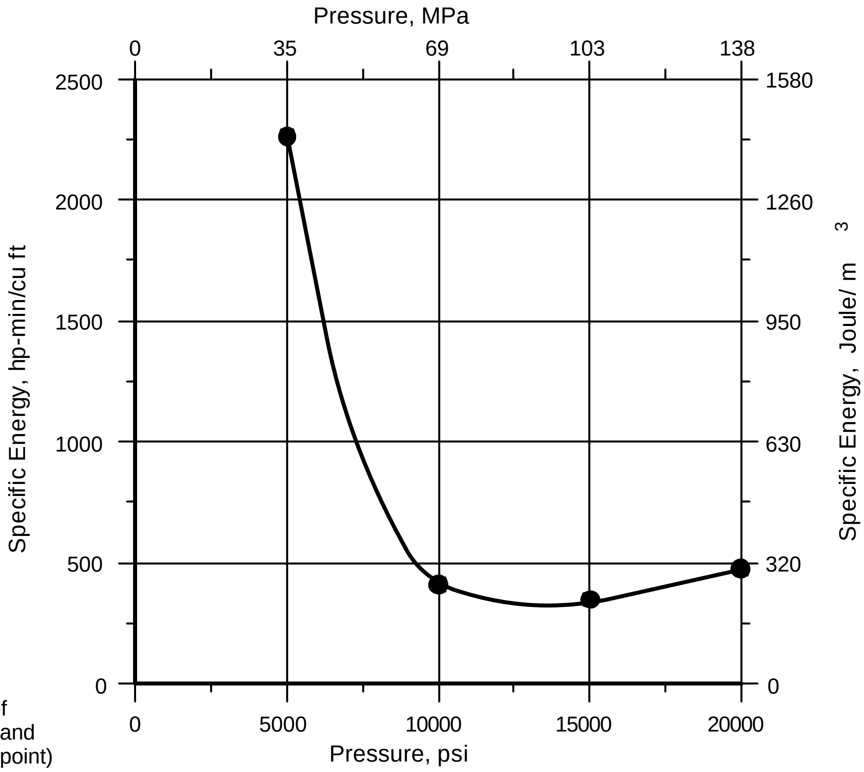
The depth of cut in the rubber material was greater at slower rotation speeds; however, the sections between the jet paths remained attached to the block. By changing the angle that the jets strike the surface, it is possible to remove slices of the material between the jet paths. In this testing, the optimum angle was found to be 60 degrees, where material removal was doubled over that removed at a 90 degree angle. The improvement was greatest at the slowest speed, and would likely continue to diminish at higher rotation speeds.



Test arrangement for rotary jet material removal
Figure 1

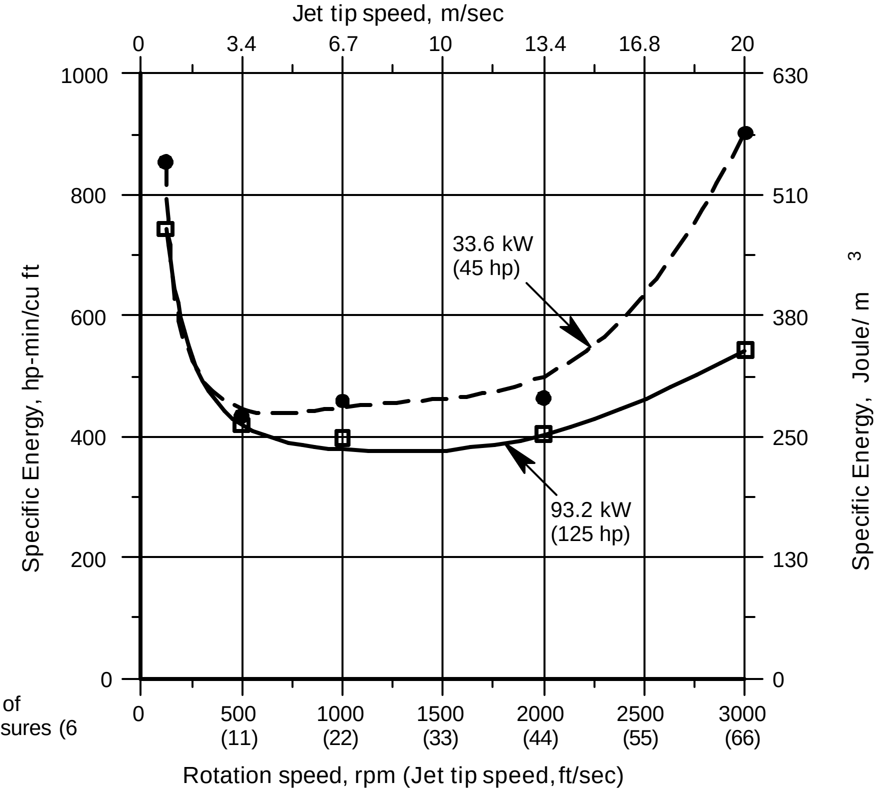
Photograph of concrete and rubber test samples

Figure 2



Concrete, avg of standoffs, flows and speeds (9 tests/point)

Effect of pressure on efficiency of concrete removal
Figure 3

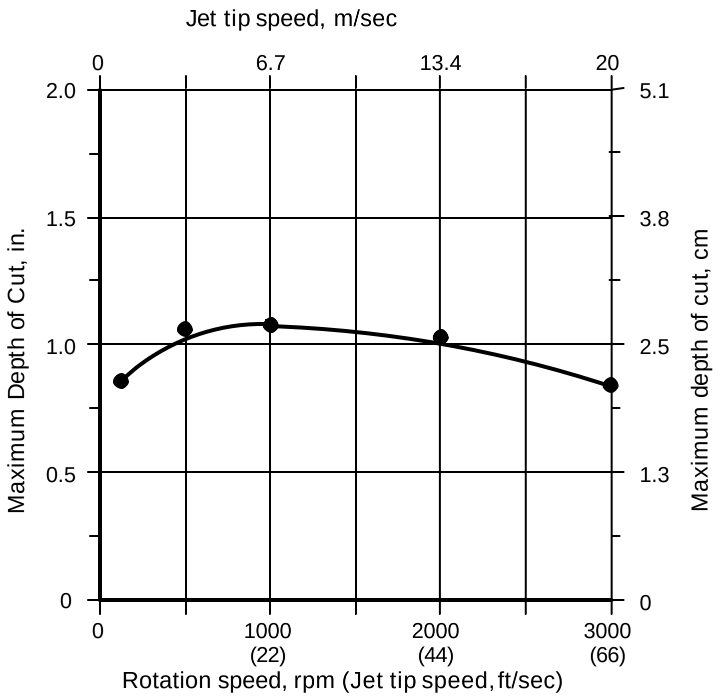


Concrete, avg of standoffs, pressures (6 tests/point)

Effect of rotation speed on efficiency of concrete removal
Figure 4

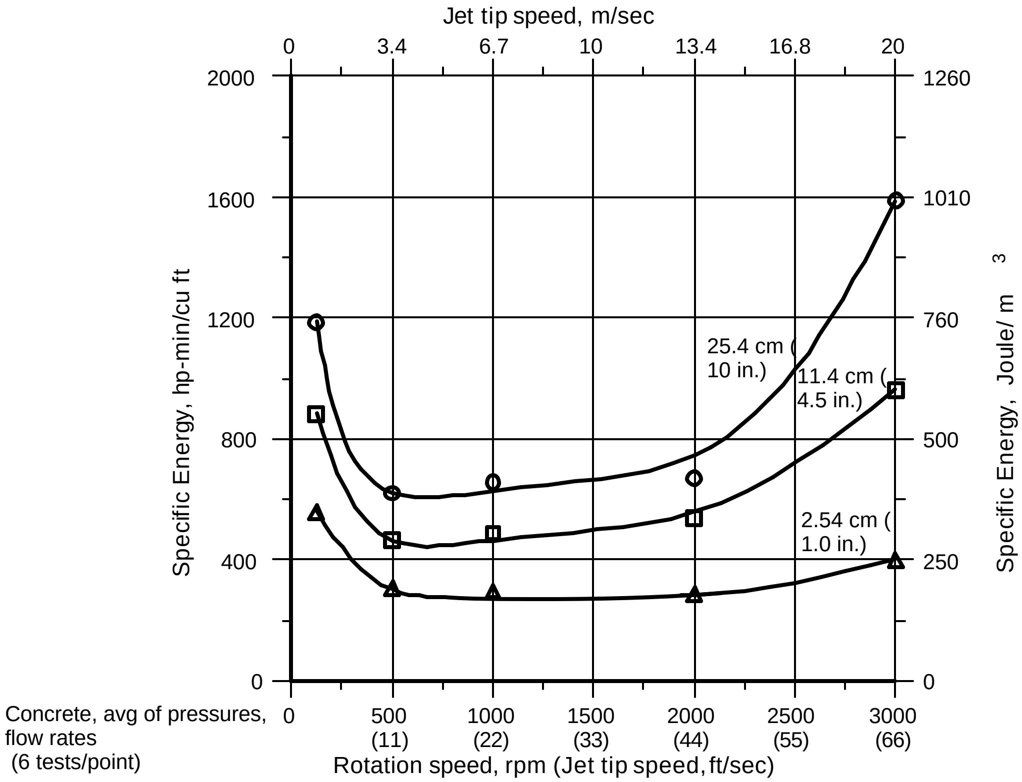
Photograph showing ribs of material not removed at 125 rpm compared to complete material removal at 1000 rpm

Figure 5

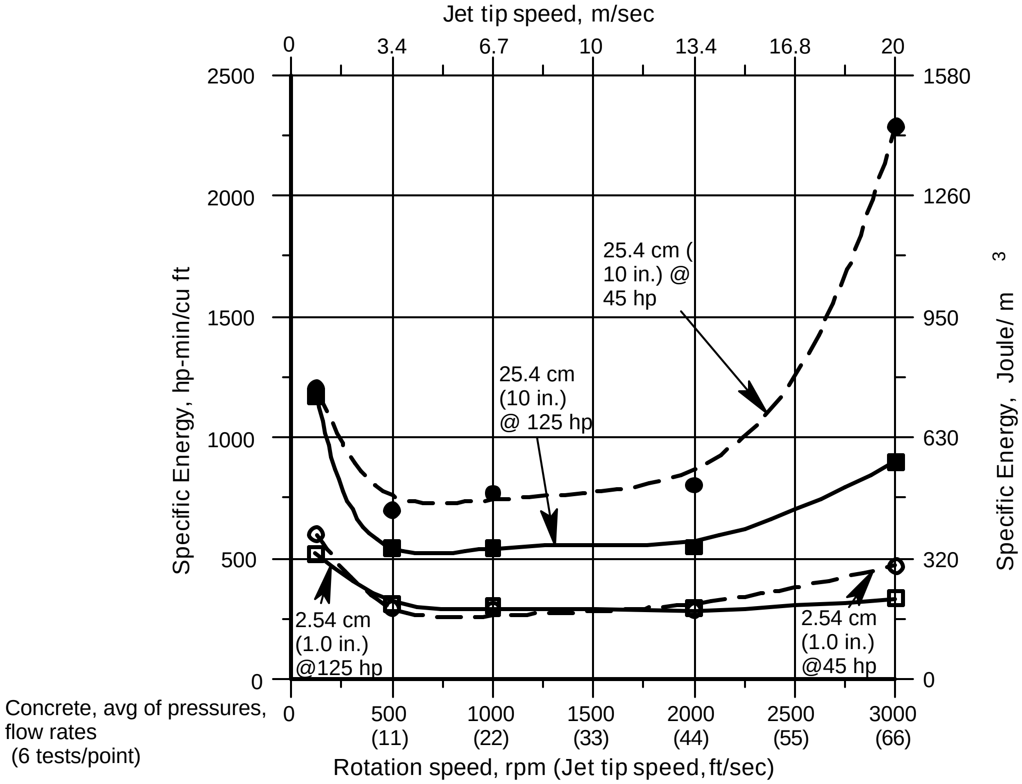


Effect of rotation speed on depth of cut in concrete

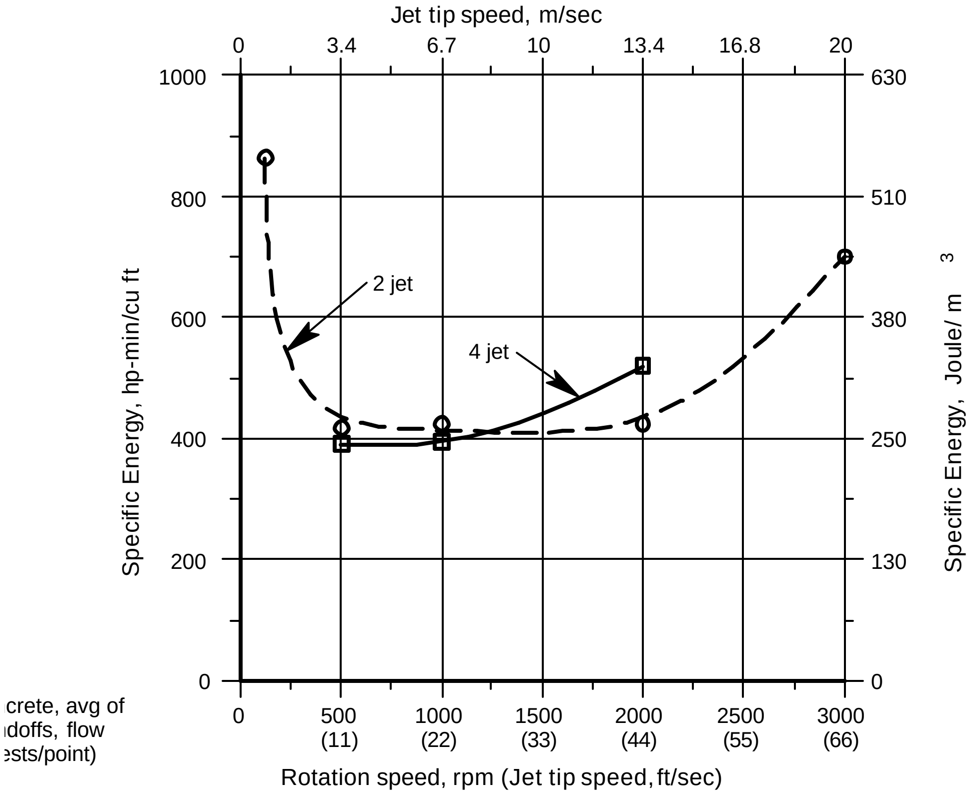
Figure 6



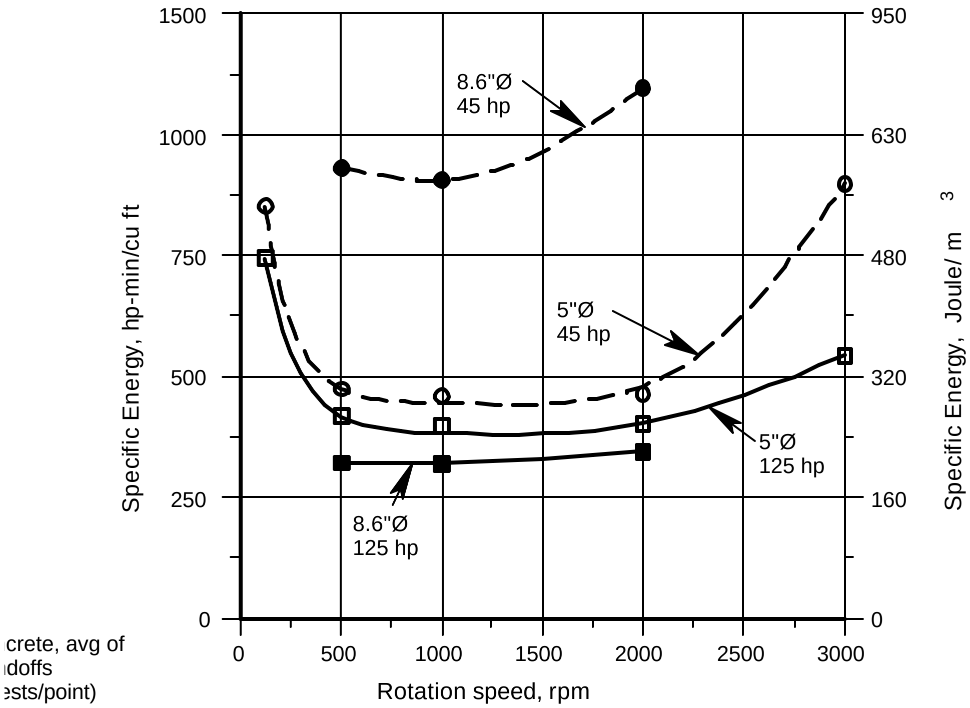
Effect of standoff and rotation speed on efficiency of concrete removal
Figure 7



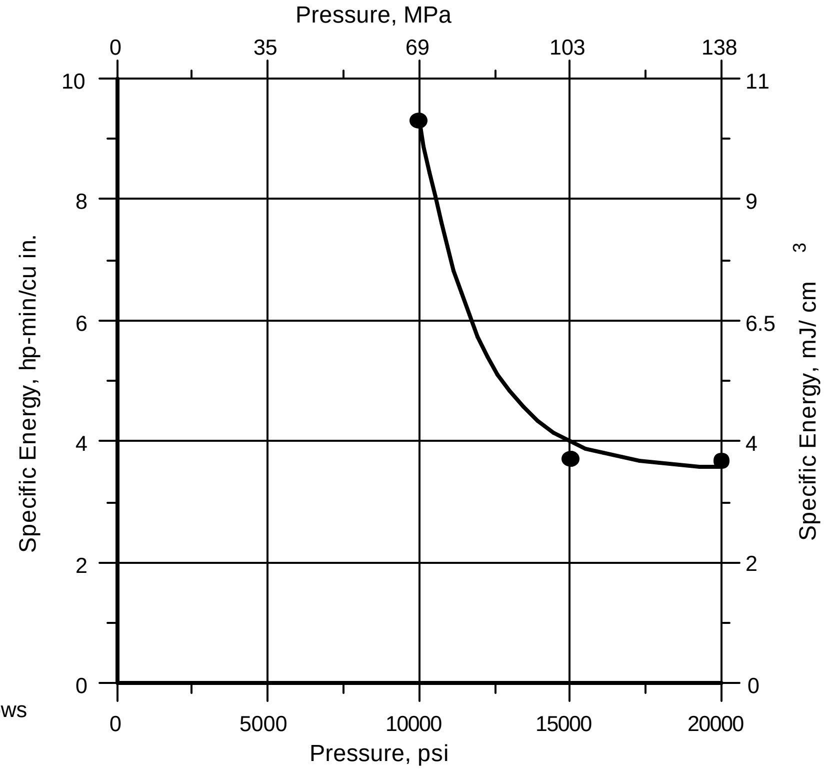
Effect of standoff at 45 and 125 hp on efficiency of concrete removal
Figure 8



Effect of dividing flow into four jets compared to two jets
Figure 9

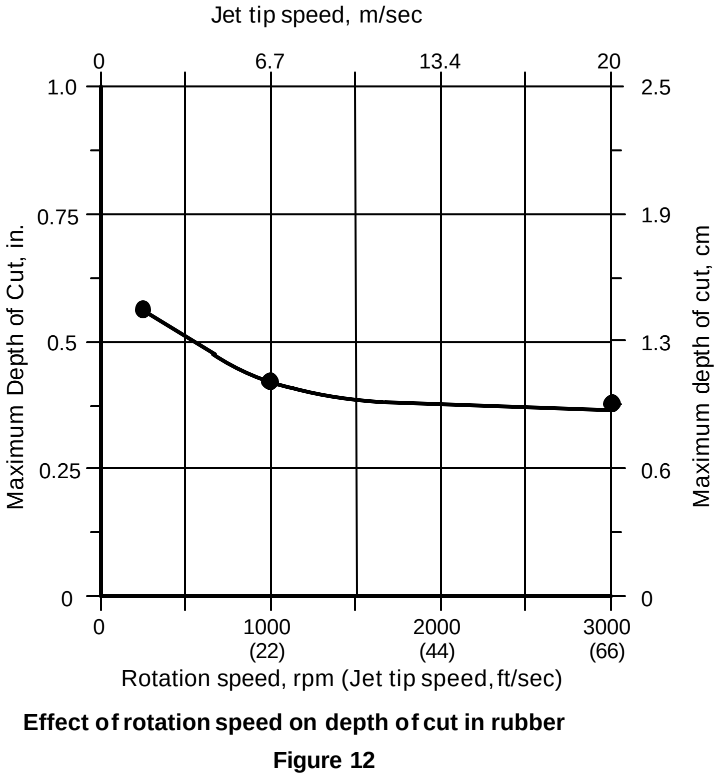


Effect of increased jet path diameter
Figure 10

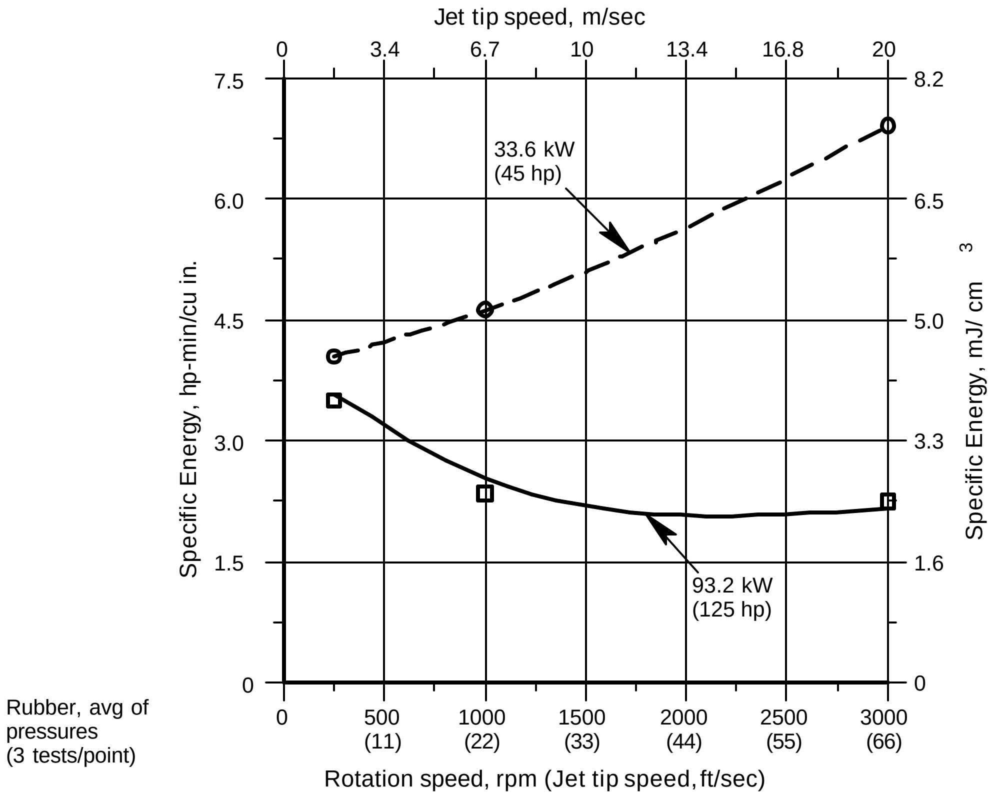


Rubber, avg of flows
and speeds
(5 tests/point)

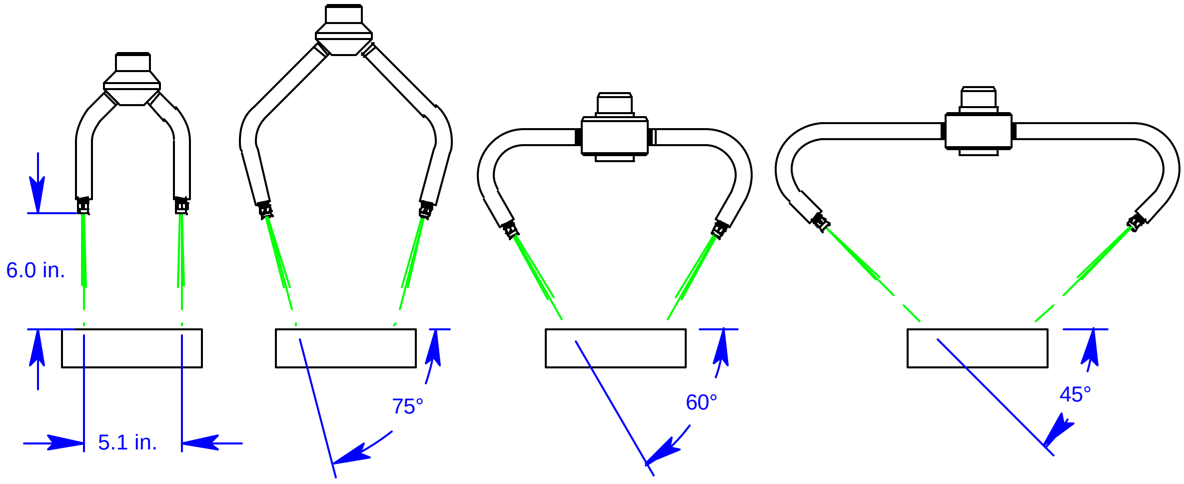
Effect of pressure on efficiency of rubber removal
Figure 11



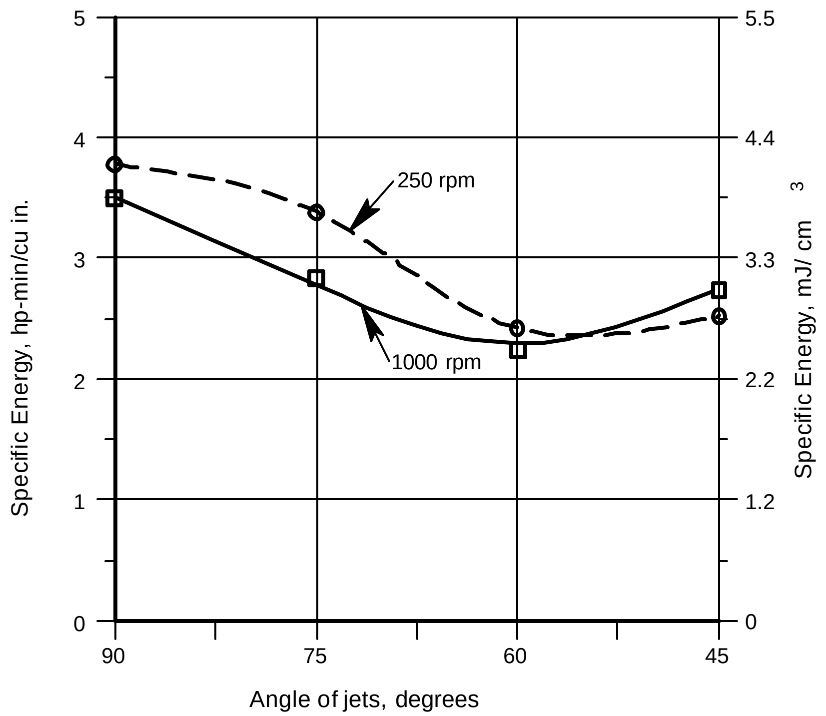
Effect of rotation speed on depth of cut in rubber
Figure 12



Effect of rotation speed on efficiency of rubber removal
Figure 13



Jet angles used in rubber removal
Figure 14



Rubber, avg of
pressures,flow
(6 tests/point)

Effect of jet angle on efficiency of rubber removal
Figure 15

Photograph showing two types of material removal in rubber; sample on left removed at 1000 and 3000 rpm, sample on right removed at 250 rpm

Figure 16