2001 WJTA American Waterjet Conference
August 18-21, 2001 • Minneapolis, Minnesota

Paper **35**

LIMITATIONS TO THE USE OF WATERJETS IN CONCRETE SUBSTRATE PREPARATION

G. Galecki, N. Maerz, A. Nanni, J. Myers
University of Missouri-Rolla
Rolla, Missouri, U.S.A.

ABSTRACT

Repair and strengthening of concrete structures with fiber reinforced materials (FRP) involves the use of externally bonded sheets, prefabricated laminates, and bars mounted near the surface. Studies have shown that the load-carrying ability of FRP materials is integrally related to the bonding characteristic of the epoxy to the substrate. This is very significant to the construction industry for identifying optimal bond characteristics since current specification requirements for the use of FRP repair and strengthening techniques have no methodology to identify these optimal conditions.

Over the years custom applications have become a standard option and some standards have to be established for specific applications. This paper discusses a roughness index of concrete surfaces produced with waterjets under different conditions.

1. INTRODUCTION

Waterjets offer advantages in the specific application of concrete removal. In-depth review of all aspects of waterjet applications in construction engineering is given by Momber (1993, 1998) and Summers (1995). Utilizing the operating flexibility of waterjets, depending on the type of work, different requirements to concrete removal rates can be achieved.

With settings for the minimum material removal, the surface can be textured or well washed at the extreme. Since Fiber Reinforced Polymer (FRP) materials have tremendous potential for repairing and strengthening structures that have deteriorated (Nanni, et al., 1993), (Myers, et al., 1999) such as columns, beams, and slabs, the interest lies in proper application of said materials. Load carrying ability of FRP materials is related to the bonding characteristic of the epoxy to the substrate. The bonding characteristic is a function of the surface roughness of the concrete, thus, identifying optimal bond characteristics is of great significance to the construction industry.

2. CONCRETE SURFACE PREPARATION

To prepare the bond surface for FRP laminating, the surface needs to be cleaned and roughened. Cleaning is required to remove foreign substances from the concrete substrate, and to remove weakened or damaged parts of the substrate. After cleaning, one of the principal factors affecting the bond behavior between the prepared concrete and epoxy is the roughness of the concrete surface. To enhance the bond characteristics of the substrate, different methods can be used to produce a rough surface. While an optimal level of roughness has not been characterized to date, preliminary bond characterization work has indicated that the level of roughness impacts the loading level at which de-lamination between the two materials occurs. Based on the initial study, improper surface preparation results in less than optimal bonding characteristic. The International Concrete Repair Institute (ICRI) has identified and prepared plastic models of nine different Concrete Surface Profiles (CSP), (International Concrete Repair Institute 1997), Fig.1. This provides a simple tool for specifying roughness. It is however a very subjective measure and lacks the objectivity that is needed.

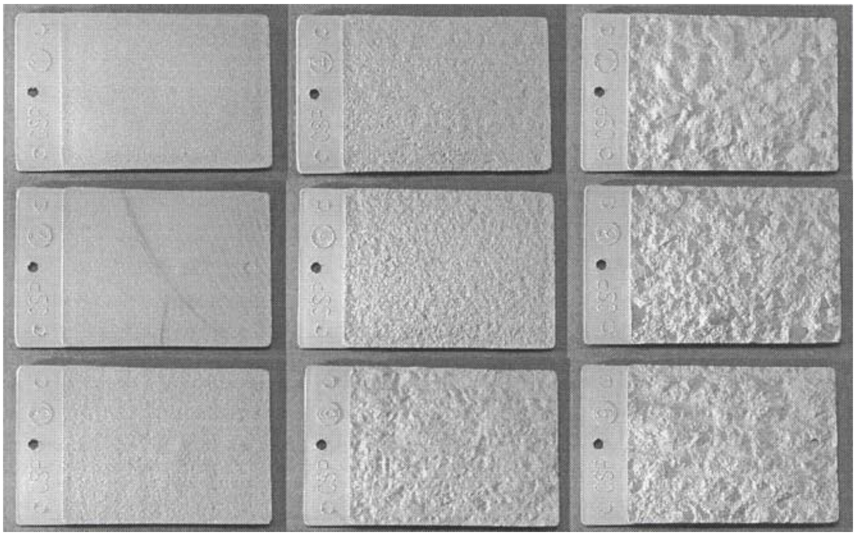

Figure 1. Plastic model concrete surface profiles. The profiles are ordered 1 to 9 in order of increasing roughness, and correspond to acid etching, grinding, light shotblast, light scarification, medium shotblast, medium scarification, heavy abrasive blast, scabbing, and heavy scarification.

Surface preparation of industrial structures is a problem. Surface preparation is the process by which sound, clean, and suitably roughened surfaces are produced on concrete substrates for the application of the specified protective system. Methods used will determine the substrate topography required for the different type of coatings. According to ICRI (International Concrete Repair Institute, 1997), method selection must be guided by the following principles of sound practice:

- The structure to be coated should not be damaged.
- The reinforcing steel should not be damaged nor its bond with the concrete loosened.
- Vibration, impact, or thermal loads applied should not weaken the concrete.

To produce a suitably roughened surface, different methods for preparing concrete surfaces can be employed. The methods of surface preparation include: detergent scrubbing, low-pressure water cleaning, acid etching, grinding, sand blasting, shot blasting, scarifying, needle scaling, scabbing, high-pressure water jetting, flame blasting, and milling. Each of these methods has its advantages and disadvantages, which need to be considered in light of existing conditions and requirements.

Though the rough surface can be produced by different methods, there is a difference in the surface quality. For instance, the surface prepared using hand held tools results in a higher probability of interface failure at pull-off test (Silfwerbrand, 1990). When compared between sand blasting, jack hammering, and water jetting methods of surface roughening, the percentage of interface failure for each of the listed methods is 38%, 31%, and 7% respectively. This is related to the profile length, which in the case of a waterjet is the longest, providing the best anchoring effect. According to Frenzel, (2001), there are three reasons why water jetting should be selected as a method of surface preparation. These reasons are environmental requirements, process economics, and health and safety issues.

Based on assumptions that concrete is a brittle material and the aggregates are stronger than the matrix, chipping and/or liberation of the aggregates can dominate the erosion mechanism of concrete. Since concrete has a porous structure, it is expected that under the load induced by waterjets, all weak bridges connecting individual voids will be damaged and washed away. This is especially important to the outer skin of concrete casting structures where high concentration of air bubbles and much less of large aggregates can be found in the surface vicinity. When a jet moves transversely over the empty space of a pore, it will fill it up creating the cushion for a new oncoming segment of the jet. The presence of water in a pore will reduce the material removal efficiency by the damping action of water cushion. This has to be considered as a positive aspect in surface roughening, contrary to hydrodemolition.

The porosity of concrete, together with other of its properties, will control to a degree, obtainable roughness. The cushioning effect of the water trapped in the pores may be different in preparation of flat surfaces in horizontal applications than in overhead or vertical applications due to the presence or lack of water in the pores. However, there is no data available on this. Also, the ratio of the jet diameter to the pore dimension and the aggregate size and type will determine the concrete resistance against water jetting.

3. EXPERIMENTAL SET UP

To produce roughness, concrete samples were moved under a single nozzle, rotating the cutting head with variable rotational speed, Fig 2. The waterjet struck the surface at 80 degrees.

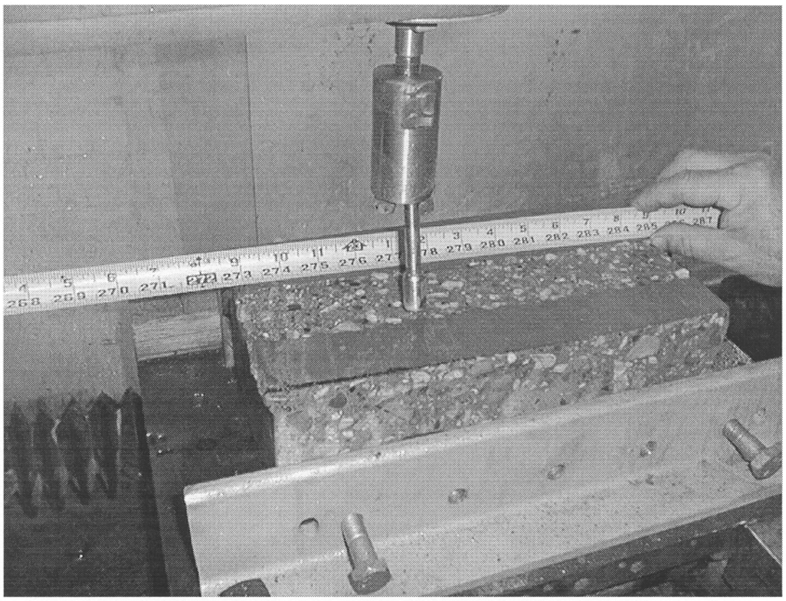

Figure 2. Test rig--general view.

3.1 Test Conditions

A stand-off distance of 6 mm, an angle of attack of 80 degrees, and a traverse speed of 0.5 m/min were kept constant during these tests.

Taking into consideration the fact that any application of waterjets is generating waste water that needs to be disposed of, it was decided to use very small diameter nozzles, Gatti type 2720 of 0.1 mm and 0.2 mm in order to produce the minimum of waste amount. Waterjets were generated under pressure levels of 70 MPa, 140 MPa, and 210 MPa. The selection of initial parameters, in part, was guided by the experience gained in the use of waterjets for drilling in sandstone (Galecki, 1983).

The relationship between the traverse speed and the rotational speed of the cutting head affects the texture produced (Galecki, 1999). To analyze this effect, the rotational speed was changed in a relatively wide range, varying from 210 rpm to 2,160 rpm. Disruption of the jets caused by the centrifugal force and its effect on the jet quality was not analyzed.

In any type of field applications, it is obvious that the set parameters might be disturbed by the outer conditions. One of these parameters, which may be affected, is stand-off distance. To simulate changes in stand-off distance, a stepped sample and an inclined sample with two inch in vertical drop were used.

3.2 Baseline Roughness

Currently, there is no means to effectively measure roughness of concrete. It can only be done by subjective comparison of the concrete surface to surface profiles in the form of plastic models provided by ICRI (International Concrete Repair Institute, 1997). In order to prepare the base-line roughness, surfaces of six concrete slabs were prepared using disk grinding and sandblasting. Then an imaging device was employed to measure the roughness of the concrete surface (Maerz, et al., 2001). Therefore, test results will no longer vary based on the disposition of an operator.

The image and roughness numbers of prepared surfaces are shown in Figure 3. Note the difficulties in distinguishing the difference in surface roughness obtained by using different methods.

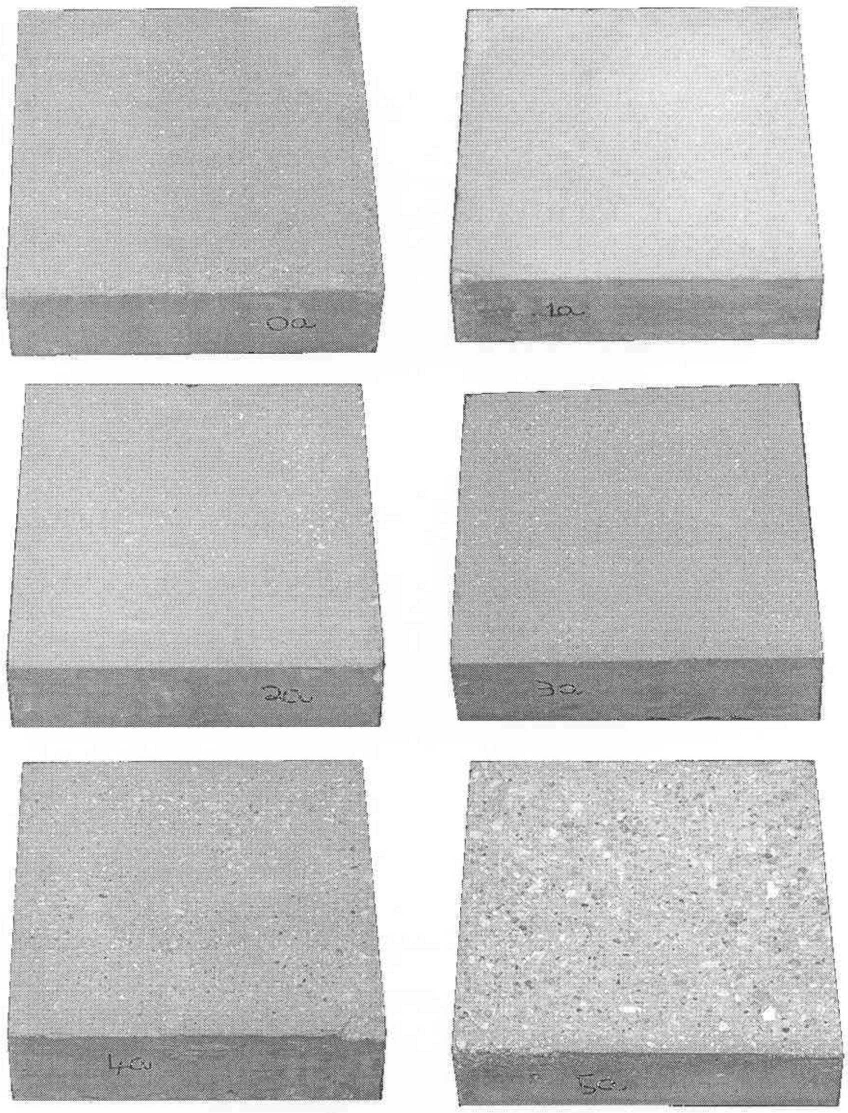

Figure 3. Concrete surfaces used for testing: block 0--surface roughened with a grinding wheel, blocks 1-5 sandblasted with an increasing duration of sandblasting media.

3.3. Water Jetting Parameters

In these preliminary tests, a combination of waterjet diameter, rotational speed of the cutting head, pressure, and stand-off distance was used. Test conditions are given in Table 1. It was decided that for studying the bonding effect between concrete and FRP, surfaces with roughness indexes corresponding to specimens 3, 7, 9, 13, and 15 were selected, Figure 4. The pull-off test results are not published in this paper, since they are part of a thesis, which has not been defended at this time.

Table 1. Test conditions and surface roughness index Ia..
Ia=average surface angle degrees

SAMPLE #	PRESSURE (MPa)	NOZZLE (mm)	ROTATIONAL SPEED (RPM)	ROUGHNESS INDEX (Ia)
1	210	0.2	1080	16.8
2	Clogged nozzle			no results
3	140	0.1	210	11.5
4	210	0.1	210	18.4
5	210	0.1	1080	15.1
6	210	0.1	1080	11
7	210	0.1	2160	11.1
8	210	0.1	360	15
9	210	0.1	360	14.8
10	140	0.1	2160	8.7
11	140	0.1	1080	10.4
12	140	0.1	360	12.6
13	140	0.1	210	13.1
14	70	0.1	210	9.7
15	70	0.1	360	9.7
16	70	0.2	360	12.2
17	105	0.2	360	14.4
18	140	0.2	360	14.8
19	140	0.2	720	13.9
20	140	0.2	360	17.3
21	140	0.2	360	N/A
22	70	0.2	360	15.7
23	140	0.2	720	16.5
24	140	0.2	1080	17.7
25	140	0.2	2160	16.6
26	140	0.2	2160*	13.1
27	140	0.2	1080*	13.9
28	140	0.2	1080*	14.9
29	140	0.2	720*	16.7
30	140	0.2	720**	13.8/13.8
31	70	0.46	720**	13.1/14.7
32	140	0.46	720**	N/A

*50 mm vertical drop
** inclined sample

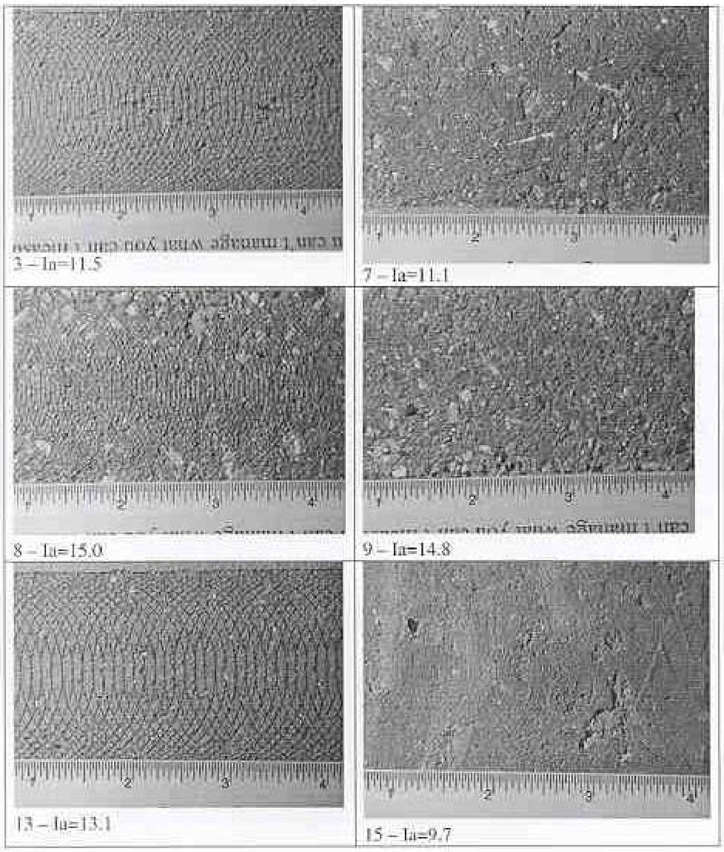

Figure 4. Images and the roughness indexes of concrete surfaces prepared under different conditions; image number corresponds to the test number in Table 1.

4. DISCUSSION OF RESULTS

Due to the complex nature of interaction between the waterjet and concrete surface, the surface roughness of the given concrete is related to all operational parameters. Though these parameters do not act independently, but as a group affecting the surface topography, attempts to discuss the influence of some main parameters on the surface roughening process with waterjets are made in the following sections.

4.1 Pressure

Material removal rate is strongly dependent on waterjet energy imparted to the cutting zone. When examining the influence of pressure only, it can be seen, that the change from 20,000 psi to 30,000 psi resulted in roughness index change from 3-Ia=11.5 to 4-Ia=18.4. A much gentler change in pressure from 105 MPa to140 MPa, resulted in a roughness index change from 17-Ia=14.4 to 18-Ia=14.8. These two sets of different conditions very well illustrate how much the surface roughness can be controlled by change in pressure.

Though the roughness index is used to determine the change in surface topography, these numbers are meaningless unless the relationship between the roughness index and the bond strength will be established. Again, the roughness index is established to objectively compare the surface condition.

4.2 Rotational Speed

Since chipping and/or liberation of the aggregates can dominate the erosion mechanism of concrete, the concrete properties (mainly the size of aggregates) will determine the pitch of the waterjet passes. The pitch will control the wash-away process of the soft matrix in order to release the harder and bigger components. The pitch of waterjets is the result of the traverse speed and the rotational speed of the cutting head.

It is important to note that the pitch of waterjet passes can be maintained in a wide range of operating parameters. The contact time between waterjets and the concrete surface will vary depending on the speeds at which the surface is roughened. The higher the surface preparation rates, the shorter the exposure time of the surface to waterjets that is needed. To illustrate the effect of the exposure time to waterjets on the surface roughness, the rotational speed was changed from 360 rpm to 2,160 rpm. The traverse speed was maintained at the same level of 0.5 m/min. As a result of these changes, the roughness index dropped from 8-Ia=15.0 to 7-Ia=11.1 (see Figure 4). As depicted in Fig.4, the influence of the rotational speed on surface roughness is significant, therefore, this parameter can be used in the process control.

Both, density, as well as the distribution of waterjet passes, contribute to the surface roughness index. The surface coverage by waterjets was studied by Galecki (1999). Since concrete is a non-homogeneous material, it can be expected that under the same conditions roughness may vary from area to area.

4.3 Nozzle Diameter

Nozzle diameter, together with jet velocity as a function of pressure, will determine the energy imparted to the collision zone on a concrete surface. Adjusting one or the other parameter, the performance the waterjet can be controlled. The questions of what and why should always arise at the beginning of any application. The environmental issues and economics of the process of applying FRP materials were the reasons why small diameter nozzles were used. Small diameter nozzles give low discharge and it is always easier and less expensive to dispose of waste in smaller quantities. For the purpose of applying FRP materials, the minimum of surface material has to be removed which can be achieved with low energy waterjets.

Although the condition for optimal bonding between epoxy and substrate is not yet known, it is obvious that excessive roughness of the surface will require larger quantities of primer, putty, and epoxy, which in turn increases the cost of the job performed.

Investigation into the relationship between the nozzle diameter and the surface roughness index was carried out with nozzle sizes of 0.1 mm to 0.2 mm at 70 MPa, in experiments 15 and 22 of Table 1. When nozzle diameter was changed from smaller to larger, the roughness index increased from 15-Ia=9.7 to 22-Ia=15.7. No data is available at the moment on how the difference in surface roughness may influence the bond strength.

4.4 Stand-Off Distance

Waterjets loose their cutting effectiveness as a function of stand-off distance. Since roughening with high pressure waterjets is a stand-off distance sensitive operation, it was decided to investigate this parameter by using stepped samples with a 50 mm vertical drop, Fig. 6. The roughness produced on the lower and upper surfaces on sample 29: 29-Ia=15.8 and 29-Ia=15.5, respectively. Closeness of these measurements overcame expectation, since subjective investigations showed a difference in surface conditions. In this particular case it was possible to show the usefulness of the imaging device.

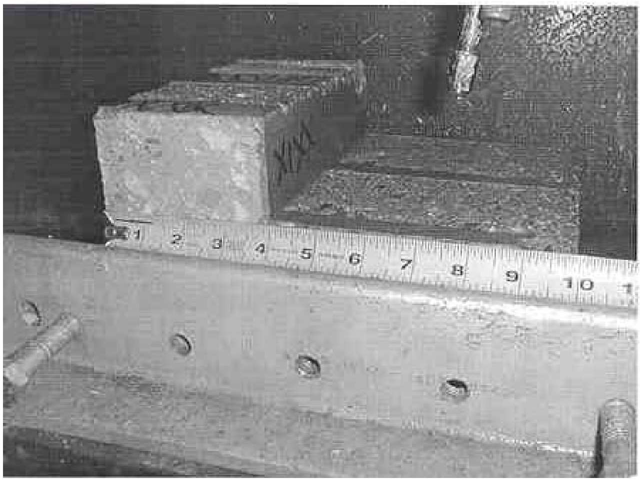

Figure 5. Stepped sample to investigate the influence of stand-off distance.

5. CONCLUSIONS

Repair and strengthening of concrete structures with fiber reinforced materials is mainly performed on existing structures with unknown properties. As expected, the properties of concrete will vary from structure to structure. As shown in previous sections, water jetting with high pressure is a very flexible process in sensitive surface preparation. It seems to be a logical approach to run a test on a concrete surface under selected parameters to identify the property of the concrete by the roughness index. Then, necessary adjustment of the operational parameters has to be made to produce the optimal surface condition. A waterjet end effector can be integrated with an imaging module for automated surface roughening.

6. ACKNOWLEDGEMENTS

The financial support by the Federal Highways Administration and American Concrete Institute is greatly appreciated. The authors are thankful to Dr. David Summers, University of Missouri - Rolla, for his valuable comments.

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