

Preparation of Rock for Supporting a Nuclear Power Plant Foundation

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Introduction

Most nuclear power plants (NPP's) are founded directly on rock at the bottom of an excavation down through overburden soils. Often with modern standardized NPP's, rock is somewhat deeper than the design base level of the NPP, necessitating fill concrete be placed between the base of the NPP foundation and the top of competent rock. Moreover, the rock surface upon which the fill concrete or the NPP foundation is placed requires treatment, with dental concrete and leveling concrete, to deal with faults, fissures, fractures, joints, inclined bedding, and the ordinary undulatory nature of the top of rock surface.

The common practice of using dental concrete and leveling concrete was developed for concrete gravity dams and simply extended and enhanced for use with NPP's. Controversial questions that arise during implementation of the practice include the following:

- What is competent rock versus, say, weathered rock?
- What is an acceptable thickness of fill concrete between the top of competent rock and the NPP concrete foundation?
- What should be the properties of the leveling concrete and the fill concrete — should one try to match the properties of the country rock or match the properties of the supported foundation or fill concrete?

This paper addresses these four questions and provides guidance on the proper techniques for preparing the rock at the bottom of an excavation to make it suitable for supporting a NPP foundation, considering both static and dynamic (earthquake) loading conditions. This paper is intended to be suitable for the special considerations of NPP's as well as foundations for dams, large mat foundations for high rise structures, LNG facilities and other industrial facilities where the rock preparation can influence the behavior of the supported structure.

1 What is “Competent” Rock?

The definition of competent rock, to some degree, depends on the desired behavior of the rock when subjected to the required bearing pressure, static and/or dynamic, or possibly the gross permeability of the rock, say in the case of a gravity dam. Here we address the relatively simple question of ‘What is “Competent” Rock in the context of nuclear power plant (NPP) foundations where the average static bearing pressure is generally in the range of 4 to 6 tons per square foot (tsf) or about 400 to 600 kPa and the peak dynamic bearing pressure is generally less than 100 tsf or about 10,000 kPa.

The desired behavior of the competent rock in this situation is to limit the settlement to acceptably low values, say, in the range of 0.5 inches to 2 inches (10 to 50 millimeters (mm)) and assure an adequate margin against bearing capacity failure of at least 2.5 to 3.0.

Our purpose is to distinguish between weathered rock and competent rock as most often a relatively thin layer of weathered rock, possibly several meters thick, overlies competent rock. Therefore, it is appropriate to distinguish between competent rock and weathered rock as regards NPP foundations.

We recommend three criteria be used to define “competent bedrock” for the purpose of NPP foundation design and construction:

1. Competent rock should be lithologically described as rock, as opposed to a soil-like, unconsolidated material, as part of the core evaluation and logging process performed by a suitably qualified engineer or geologist *immediately* after core extraction from a borehole during the drilling process. Note that we emphasize the need to log the core immediately, meaning minutes, after the core is extracted to prevent any weathering or degradation of the core as it is transported from the borehole to the core shed. Also, a pocket penetrometer can be useful for this evaluation.
2. The lithological description of competent rock must indicate that the extracted core is fresh or slightly weathered. This implies that the geologist must distinguish between country rock and boulders often encountered overlying rock, say, in glacial environment.
3. Competent rock must demonstrate resistance to force from a split-barrel sampler equal to at least 50 blows per 6 inches (150 mm) of penetration as measured via a standard penetration test (SPT) that employs an automatic trip hammer, in accordance with ASTM International (ASTM) 1586.

The definition also allows for the possibility that competent rock may have fissures, fractures, joints, bedding planes or offsets that are weathered, open, and/or filled with unconsolidated soil-like materials – these features do not preclude the rock from being classified as competent if it meets the three criteria described above. These localized flaws are to be treated with dental concrete and/or grout following the conventional practice for foundation preparation.

2 What is an acceptable thickness of fill concrete?

In the general situation the level of the basemat of the NPP nuclear island for a standard NPP design, such as the AP1000, is 12 m to 14 m below final plant grade or as deep as 28 m below final plant grade for other standard designs. Rarely, if ever, does the top of competent rock coincide with this level. If competent rock is relatively shallow, then rock must be excavated to an acceptable level to match the bottom of the NPP basemat. In the situation where the top of competent rock is deeper than the design level of the NPP basemat, then excavation of the overburden down to competent rock, followed by dental treatment and a layer of fill concrete between the top of competent rock and the NPP basemat foundation is required.

The issue addressed by this question is the allowable thickness of the fill concrete. The technical issues to be considered include the following:

- At what thickness of fill concrete is the dynamic behavior of the NPP perturbed over and above the situation where the competent rock is directly under the basemat?
- Is there a thickness of fill concrete where the heat of hydration is so high that cracking of the concrete cannot be limited or controlled?
- Does the thickness of the fill concrete affect the static settlement of the NPP?
- Does reinforcing steel have to be included in the design of the fill concrete?

The fill concrete is meant to replace competent rock that has been removed by natural means or simply not deposited to a high enough level at the site. In any event the fill concrete is meant to simply convert the actual level of competent rock to a more desirable level. If the fill concrete has properties equal to the competent rock or “stiffer” than the competent rock, the fill will not change the ground motion attributed to the top of competent rock. By stiffness, we mean the shear wave velocity. Therefore, there is no thickness within the normal range of dimensions of a NPP basemat that the dynamic behavior of the NPP will be perturbed.

As regards the heat of hydration, generally accepted practices and concrete codes indicate that temperature control of concrete placements is necessary whenever the placement is more than a meter or so such that mass concrete placement procedures should be followed. These procedures can include one or more of the following:

- Use of a pozzolan, such as flyash, to replace some of the cement in the mix, such as with roller compacted concrete.
- Limit on the thickness of any single placement to not more than one or two meters.
- Placement of the fill concrete at night only, possibly along with misters on the surface.
- Placement of the fill concrete in winter months if practical from a schedule and logistics perspective.
- Use of ice water in the mix, covered conveyors, stockpile management, and/or sprayers on the stockpiles.
- Monitoring and control of temperature with thermocouples and other temperature measurement instruments.

With a combination of the above, supplemented with modern comprehensive thermal analysis, cooling of the concrete with circulating buried cooling water pipes should not be necessary. Also, following these practices eliminates constraints on the thickness of fill concrete.

2.1 What should be the properties of the leveling concrete and the fill concrete?

The primary question is whether one should try to match the properties of the fill concrete to those of the country rock or match the properties of the fill concrete to the concrete in the supported foundation. In the case of a gravity dam, should one match the properties of the fill concrete (and leveling concrete) to the properties of the rock or the properties of the dam?

Recall from above that the fill concrete is simply replacing “missing” rock; consequently, the fill concrete should have stiffness and strength properties that mimic or exceed the stiffness properties of the country rock. This implies that that shear wave velocity, being a measure of stiffness for both static and dynamic behavior, of the fill concrete should equal or exceed the shear wave velocity of the country rock.

Also the fill concrete should have an unconfined compressive strength equal to or exceeding the unconfined compressive strength of the country rock. The fill concrete need not be reinforced as it will have a tensile strength equal to about 10% of the unconfined compressive strength and consequently, it will equal or exceed that of the country rock.

Given this approach of matching properties, the dynamic behavior and static settlement properties will be equal to or better than that if the fill concrete did not exist, i.e., the NPP basement was found directly on competent rock.

3 Preparation of the Rock Surface

Practically all foundations bearing directly on rock have some form of dental concrete, leveling concrete, and fill concrete between the competent rock and the NPP basemat foundation. By way of example we show several case history photos of what should be expected.

Figure 1 shows the early stages of rock cleanup and preparation at the level where competent rock was defined on the basis of borings and acoustic televiewer logs.



Fig. 1. Rock Clean-up prior to Dental Concrete and Leveling Concrete

Figure 2 shows the type of equipment and labor-intensive effort required to properly prepare the rock to receive dental concrete and leveling concrete, specifically air and water lances and vacuum trucks.



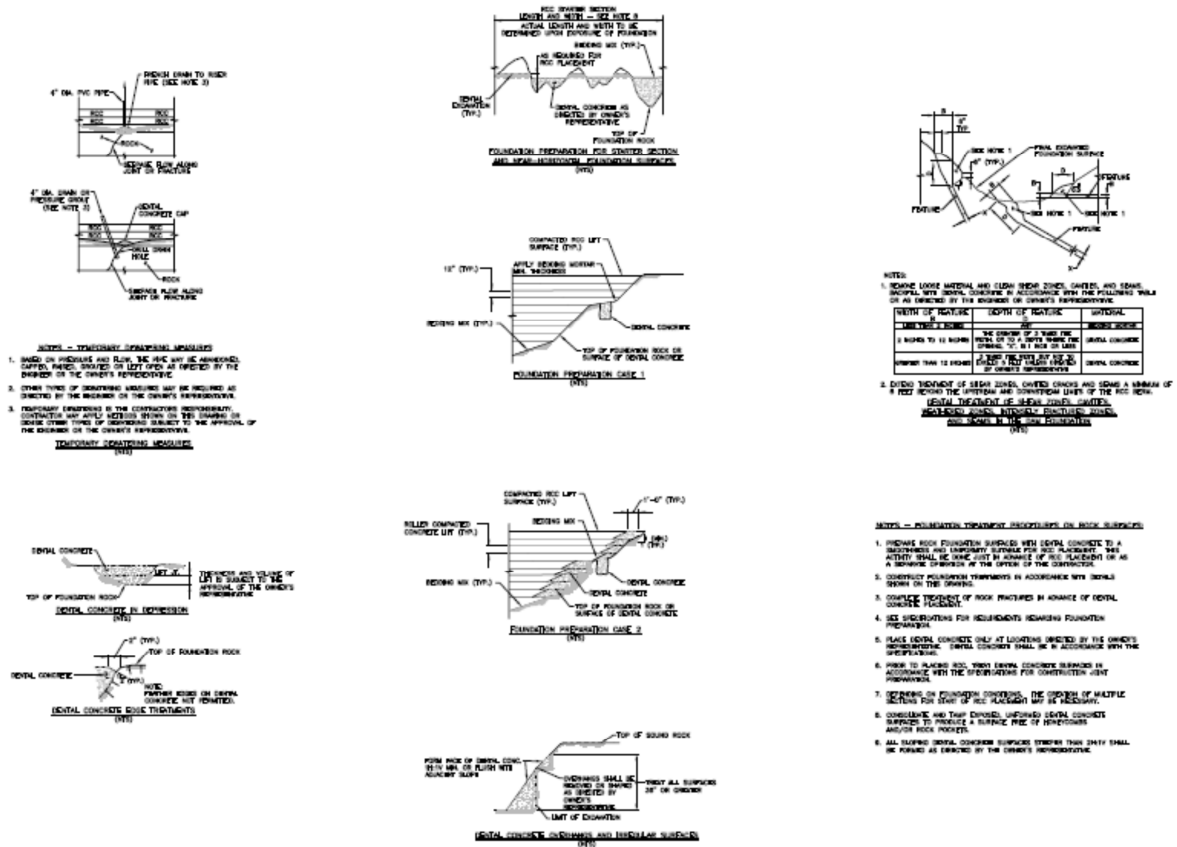
Fig. 2. Rock Preparation with Vacuum Trucks and Air Lances

Figure 3 shows dental concrete and leveling concrete in a weathered zone encountered in the foundation bottom after exposure during excavation. The leveling concrete in this case was several meters thick, requiring consideration of the temperature rise associated with the heat of hydration.



Fig. 3. Dental Concrete and Leveling Concrete Being Placed Adjacent a Mafic Dike

The overall approach to rock preparation involves a significant amount of preparatory work in accordance with generally accepted details, some of which are illustrated below in **Figure 4**.



GENERIC FOUNDATION TREATMENT DETAILS

Fig. 4. Rock Preparation Details

We provide in Appendix A to this paper a set of typical Construction Specifications that the author has used on the sites where all of the examples are illustrated. Of course, these specifications should be revised to match the actual conditions at a specific site.

4 Are there any licensing precedents for fill concrete at NPP's?

Regulators do not usually look at this issue, we believe, because it is viewed as conventional construction practice that does not deter from the behavior of the foundation. Nevertheless, the authors have done some research on the topic and can cite the following:

Fill concrete, actually roller compacted concrete referred to as a "bridging mat" below in **Figure 5**, having a thickness of about 11 m is being used for a new NPP on the west coast of Florida, USA to support two AP1000 units.

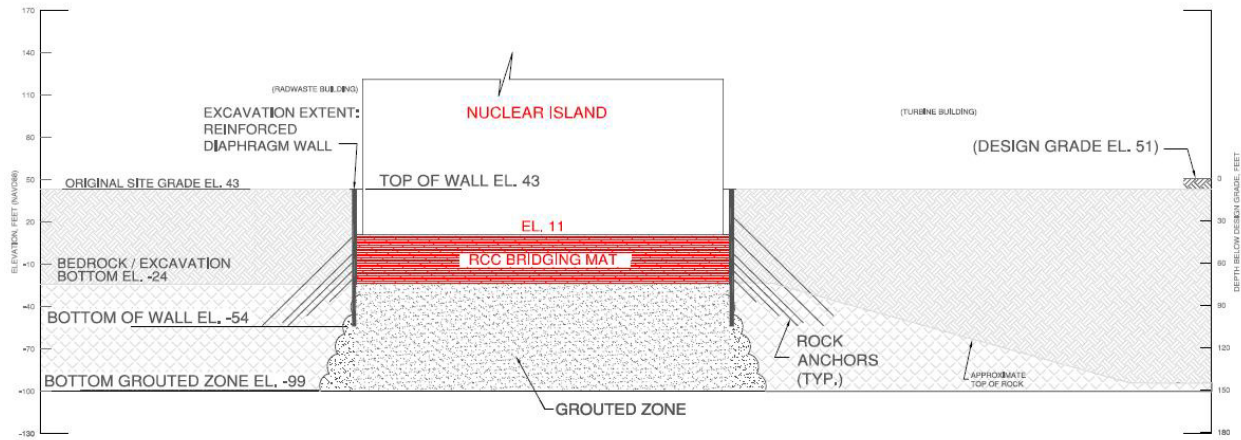


Fig. 5. NPP Foundation with 11 m of Fill Concrete

In the case shown in **Figure 6**, the RCC bridging mat is bearing on a grouted zone of limestone.

Conventional concrete having a thickness of about 6 m is being used for a new NPP on the east coast of Florida, USA to support two AP1000 units.

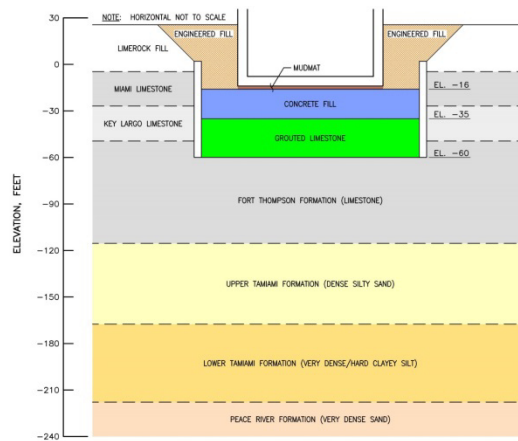


Fig. 6. NPP Foundation with 6 m of Fill Concrete

The third example in **Figure 7** is an NPP founded on metamorphic rock that is highly undulatory due to weathering of the country rock.

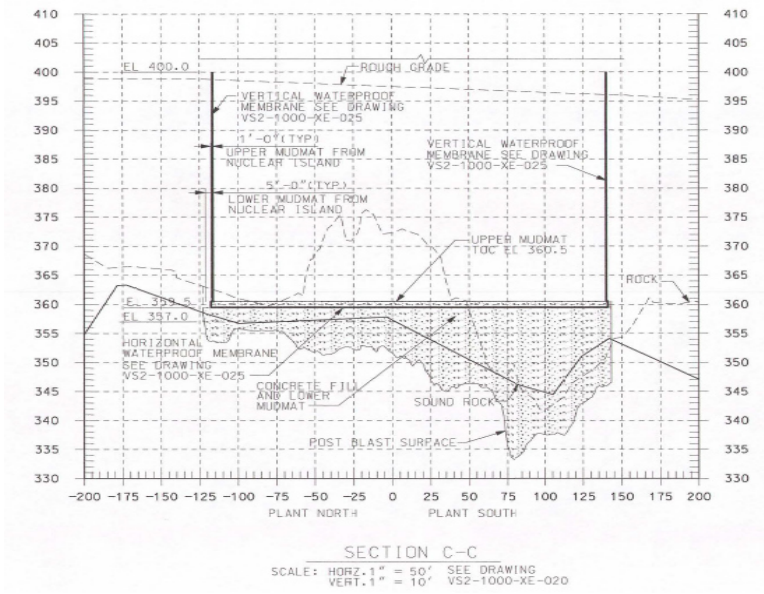


Fig. 7. NPP Foundation on Fill Concrete with Undulatory Competent Rock Surface

The case in **Figure 7** illustrates very well the desirability of matching or exceeding the stiffness and strength properties of the fill concrete to the country rock to assure a reasonably uniform foundation condition.

Concluding Remarks

The author draws the following conclusions and recommendations for the use of fill concrete between the basemat of a NPP and competent rock.

- Regardless of the thickness of fill concrete required to suit the field conditions and the NPP design, dental concrete and leveling concrete should be anticipated.
- No technical reasons exist for limiting the thickness of the fill concrete, so long as the thickness is generally less than the width of the basemat foundation. For cases where the thickness is greater than the width, the author recommends special seismic and structural analysis.
- The stiffness and strength properties of the fill concrete should equal or exceed the same properties of the competent country rock.
- If the thickness of the fill concrete exceeds about 2 m, general construction practices and concrete codes may dictate special techniques for controlling the temperature rise associated with cement heat of hydration.
- There is ample precedent in practice with NPP's indicating that 10 m of fill concrete is not a licensing or engineering issue.

APPENDIX A

CONSTRUCTION SPECIFICATOINS ROCK FOUNDATION PREPARATION

PART 1 - GENERAL

1.1 DESCRIPTION

1.1.1 This section describes the treatment procedures for the shear zones, weathered areas, and other unsuitable areas of the rock foundation. The work described in this section is critical to the performance of the structure and the Contractor should perform this work carefully to ensure that all unsuitable materials are removed to the extent specified and that the surrounding intact rock is not damaged during the treatment process. The rock foundation preparation may involve an intensive cleaning and remediation effort, and the Contractor must plan for this effort accordingly.

1.2 SUBMITTALS

Submit a foundation treatment plan that sets forth the proposed procedures and sequences for performance of the Work. The plan shall be by rock type, contact zone, weathered area, or other unsuitable area. The plan shall be submitted at least 14 days before any foundation preparation work begins. The plan shall include, but not be limited to, the following information:

- 1.3.1 The equipment and construction procedures to be used in excavating the various features identified for treatment.
- 1.3.2 Drawings or sketches of the treatment area showing how the Contractor plans to excavate and treat these areas including overhangs.
- 1.3.3 The vertical and horizontal alignment controls to be used to ensure that the treatments are performed as specified.
- 1.3.4 Details of how the Contractor plans to control water within the excavation prism.
- 1.3.5 Details of how the treatment excavation will be performed to ensure that the rock at foundation grade is not disturbed.
- 1.3.6 Details of how the dental concrete will be placed.
- 1.3.7 The proposed work schedule.

PART 2 – EXECUTION

Dental concrete shall conform to the requirements as specified in the Specification for Cast in Place Concrete. – CAST-IN-PLACE STRUCTURAL CONCRETE.

PART 3 – MATERIALS

3.1 OWNER'S REPRESENTATIVE ACCEPTANCE

3.1.1 Foundation treatment work shall be performed in areas as directed by the Owner's Representative. Following rock excavation by the Contractor, the Owner's Representative will conduct a visual inspection to determine whether all unsuitable material has been removed. The Owner's Representative shall be notified three (3) days prior to completion of all rock excavation within the acceptance section. Within three (3) days of this notification, the Owner's Representative will inspect the work and determine

whether the final foundation cleanup may proceed or if additional rock excavation or treatment is needed. Once the Owner's Representative approves the work, the Contractor may proceed with the final foundation clean-up and dental concrete placement.

- 3.1.2 Foundation areas that have been excavated and cleaned will require approval by the Owner's Representative before any placement of material. The Contractor shall notify the Owner's Representative at least 72 hours before the areas are ready for inspection. The Contractor shall establish a grid system on 10-foot centers (using the dam axis as the baseline for the system) to assist in defining areas that are ready for inspection or have been approved for the Owner's Representative to map the foundation. The Owner's Representative will have the final and undisputed decision on the quality and acceptability of the foundation cleaning. The Contractor shall allow the Owner's Representative to inspect the foundation surface in a safe manner, undisturbed by moving equipment or other hazardous operations.

3.2 ADDITIONAL ROCK EXCAVATION

- 3.2.1 The Contractor shall be responsible for the protection of all persons and equipment from falling or sliding rock at all times. It is the Contractor's responsibility to maintain his protective measures and shall immediately replace any damaged elements. All final slopes and grades shall be protected from equipment damage and shall not be excessively scaled.
- 3.2.2 Additional Rock Excavation will primarily be in weathered and fractured rock, open fractures, and along lithologic contacts with equal hardness. Due to the variable nature of the treatment areas, however, the Contractor should also anticipate placing leveling concrete to shape irregularities at the rock surface. Some excavation operations may be conducted on relatively steep slopes and the Contractor shall account for any extra effort required to safely work on these slopes.
- 3.2.3 Excavation shall be performed to the lines, grades, slopes, and dimensions shown on the Plans or to such depths and dimensions directed by the Owner's Representative that may be required to provide satisfactory foundation treatments. The Owner's Representative reserves the right to increase or decrease the length or depth of any excavation or treatment.
- 3.2.4 All additional excavation shall be done using mechanical and hand equipment. Drilling and blasting is not allowed as an excavation method for this work unless explicitly approved in writing by the Owner's Representative in advance and so long as all necessary permits are in-hand. Any work method causing damage to the surrounding, intact foundation materials shall be stopped immediately and remediated as directed by the Owner's Representative.
- 3.2.5 The Contractor shall scale the entire foundation prism to remove all loose rock slabs, rock wedges, jutting points, or debris. Scaling shall be performed by approved hand or mechanical methods, such as barring and wedging, as necessary.
- 3.2.6 Areas of unstable material may be encountered within the foundation prism. This may occur in, but is not limited to, areas where intensely weathered rock, weathered rock, weathered dikes, and fracture zones are encountered. The Contractor is responsible for ensuring that all excavations and excavation slopes are stable.
- 3.2.7 Material from required excavations shall not be used to create aggregate for concrete production unless approved by the Owner's Representative. Materials suitable for aggregate production shall be hauled to the aggregate stockpile. Unsuitable materials will be utilized elsewhere on the site for beneficial use. Stockpiling and re-handling of these materials should be anticipated.

3.3 FOUNDATION TREATMENTS

- 3.3.1 Treatment shall be applied to any shear, shear zone, fracture, or weathered area located within the foundation prism or identified by the Owner's Representative. Shears shall be excavated to a depth as shown on the plans. Due to the uneven nature of weathered zones, the limits of excavation beneath the ground surface are variable and the Owner's Representative may direct additional excavation or terminate the excavation based on the conditions encountered.
- 3.3.2 Remove all overhangs from foundation areas as shown and as required. Shape such surfaces to the slope shown by means of drilling, barring, or wedging. The method to be used shall be subject to approval of the Owner's Representative.

3.4 FOUNDATION PREPARATION AND CLEANING

- 3.4.1 Before starting the foundation treatments, an initial foundation cleanup shall be done to remove soil, loose rock, and debris remaining from the excavation operations. The purpose of this cleanup is to clean the foundation sufficiently to accurately identify, delineate, and map all features that require treatment. This cleanup is not to prepare the foundation surface for concrete placement. This work shall be performed using picks, crowbars, shovels, brooms, air hammers, pressurized air or water, large vacuums, light power tools, or other approved equipment. No blasting will be allowed unless approved by the Owner's Representative in writing in advance and all necessary permits are in hand.
- 3.4.2 Prior to placing roller compacted concrete on the foundation and against abutments, the exposed foundation material shall be filled with dental concrete (if necessary), shaped (if necessary), and prepared. A thin placement of conventional concrete or shotcrete may be used where directed or approved to protect the prepared foundation from exposure and damage. Gravel and weathered rock or soil foundations designed to receive concrete shall be flat, compacted, and damp. No foundation or abutment area will be covered with any concrete, bedding, mix, or dental fill until it has been accepted by the Owner's Representative. A bedding mix with properties as defined in Section 3.1 shall be placed at the interface between the rock foundation or hardened conventional concrete and the concrete mixes. It shall also be used between all concrete layers as directed to limits required by the Drawings.
- 3.4.3 Foundation Shaping and Filling: Shaping by minor rock excavation (trimming) of obtrusive high points and overhangs, and by filling with conventional dental fill concrete of depressions into which concrete cannot be thoroughly compacted, will be required. Depending on the location, size, shape, and rock quality, trimming may necessitate any one or a combination of the following methods: mechanical ripping, scaling by hand pry bars, jackhammers, surface charges, or small shots of stemmed dynamite in drilled holes. Dental fill concrete may require rough face forming. Curing for dental concrete placed for filling voids in the foundation is not required except to cover the placement with burlap or sheeting for one (1) day.
- 3.4.4 Foundation Final Clean-Up: After receiving approval from the Owner's Representative and prior to placing any concrete or bedding mix, the surface shall be cleaned of loose, unkeyed, and deteriorated rock; all mud, silt accumulations, vegetation, grease and spilled oils; and frozen materials, accumulations of gravels, sands, and loose rock fragments; laitance that may have accumulated on dental concrete, and any other detrimental material. In addition, pockets of fines, sand, rock rubble, gravel, and other objectionable material shall be removed from the foundation including areas of depression, large crevices, and open rock joints. Overhangs, vertical faces, and

irregularities in the rock shall be trimmed to form a reasonably uniform slope. This work shall be performed using picks, crowbars, shoveled, brooms, air hammers, pressurized air or water, large vacuums, light power tools, or other approved equipment. No blasting will be allowed. The foundation shall be maintained in a clean condition until the placement of concrete. The Contractor shall be liable for repairs to damaged dental concrete due to subsequent operations. All surfaces upon which concrete or any bedding mix is placed shall be damp and at a surface temperature in excess of **35** degrees F. The Contractor shall have available adequate equipment for necessary air, air/water, and pressure water jetting of the foundation.

3.5 LEVELING CONCRETE

- 3.5.1 Foundation excavation and preparation for leveling concrete shall be approved by the Owner's Representative in writing prior to placement of leveling concrete. Leveling concrete shall be placed after final foundation cleanup in areas designated and detailed on Contract Drawings.
- 3.5.2 Leveling concrete shall be utilized to fill irregularities at the rock foundation surface so an effective bond and seepage barrier between rock and concrete interface is achieved, filling all corners, and eliminating rock pockets. Leveling concrete shall be vibrated in place and consolidated throughout its entire depth. Leveling concrete shall be cured in accordance with Specification for CAST-IN-PLACE STRUCTURAL CONCRETE.

CONCRETE shall not be placed on leveling concrete without the approval of the Owner's Representative.

3.6 DENTAL CONCRETE

- 3.6.1 Concrete shall be used to fill the excavated treatment areas, joints, cavities, depressions, and overhangs, as specified by the Owner's Representative. Prior to placement, all surfaces shall be thoroughly cleaned as specified herein. The concrete materials, mixes, and placements shall conform to the Specification for – CAST-IN-PLACE STRUCTURAL CONCRETE or as directed by the Owner's Representative.
- 3.6.2 Place dental concrete as required to form a tight, unfractured surface against which structural or CONCRETE can be satisfactorily placed and consolidated. The Owner's Representative will determine the limits for placement of dental concrete.

END OF SECTION