leaked, allowing groundwater in and undesirable loss of valuable water supplies. Care should be taken in seal welding grout plugs, as the differential heat application can cause grout plugs to crack and leak.

7.5 Backfill Mix Designs

Backfill mix designs vary depending on the application, method of placement, strength requirements, placement conditions, and other project-specific properties of the in-place material. The quantities and types of ingredients used to batch the backfill must be carefully selected to meet project needs. Trial batches must be mixed for workability and contract compliance. This section describes mix designs for grout and concrete, cellular concrete, and flowable fill.

7.5.1 Mix Designs for Grout and Concrete

The re are several standard requirements for backfilling precast concrete segmental liners. The backfill grout should be workable for extended periods. The time from batching to placement may be up to several hours. The amount of time during which the grout must remain workable depends on the anticipated TBM advance rate and the anticipated delivery time from the batching location to the injection point.

The backfill grout mix must be designed to ensure that the fresh grout will resist water infiltration and washout prior to reaching initial set. The grout mix also must be designed to resist segregation and bleeding. The grout may be transported without agitation over temporary track and be subject to continuous vibration that will tend to settle out the denser grout ingredients. This may result in non-uniform grout being delivered to the point of placement and possible plugging of delivery lines and fittings. The grout must be stiff enough to remain in place behind the segments but fluid enough to flow through the pumps, hoses, piping, and fitting and into the annulus. Once in place, the grout should set and gain strength rapidly. The grout should have at least the same or greater compressive strength as the in situ strength of the surrounding soil and should remain stable under water. For rock tunnels utilizing concrete segments, backfill grout should have a compressive strength at least equal to the compressive strength of the concrete segment liner. Typical minimum backfill grout compressive strength requirements for tunnels excavated in soil are 1,380 kPa (200 psi) in 24 hr and 3,450 kPa (500 psi) in 28 days. Typical backfill grout compressive strength requirements for tunnels in rock are 4,830 kPa (700 psi) in 24 hr and 21 to 35 MPa (3,000 to 5,000 psi) in 28 days. Finally, the grout should be produced as economically as possible by maximizing ingredients such as flyash and sand, while minimizing the use of cement and admixtures.

Backfill grout for TBM precast liners is typically a combination of cement, flyash, bentonite, sand, water, and admixtures. Because the backfill is usually a unique assortment of ingredients that have never been mixed together before, a combination of analysis and trial batches is required. Even if a backfill mix has been used before for another project, geographic variation of ingredients will require retesting of the mix using trial batches. The goal is to produce a backfill that is as dense as possible, yet can be pumped and placed using the least amount of mix water. Any mix water added beyond the minimum amount required to make the backfill pumpable and flowable will increase segregation and shrinkage during curing, contribute to the porosity of the in-place backfill, and reduce the final compressive strength. In grout backfill mixes, bentonite is usually added to the mix to minimize segregation, which can cause line plugging after a pumping interruption. Bentonite also keeps the grout from losing water and stiffening up when under injection pressure.

The first step in designing a backfill grout mix is to gather information on all the possible ingredients. More than one source of each ingredient should be obtained when possible to maximize the possibility of developing an efficient grout. Type F flyash is usually favored because it is relatively inert and adds sulphate resistance. Type II cement is often used because it has a slightly slower set time than Type I and is moderately sulphate resistant. Saturation points should be determined with different ratios of flyash and cement, starting with 100-percent cement by weight and working toward 100-percent flyash by weight in 20-percent increments. Plot all the curves for each combination of cement and flyash to find the one with the least water demand. Sometimes Type II cement is not readily available and alternatives should be allowed. In many cases, Type C flyash is the only available material. The chemical makeup of both Type F and Type C varies from power plant to power plant. Sometimes the Type C is more preferable. Availability is very important, as is the availability of Type II cement.

The basic grout mixture should be determined by combining the selected cementitious materials (cement and flyash) with sand in different ratios and determining the saturation point for each ratio. Next, a 50:50 mix of sand and cementitious material should be used, varying the combination from 50-percent cementitious material by weight to 100 percent to get data points in the 10- to 40-percent range. Plotting the water demand against percent of cementitious material will show there is a point of minimum water demand and highest solids content.

The basic grout mix will be very stiff, having the maximum density possible while using the least amount of water. A more flowable grout will require additional water, which also will increase voids, segregation, bleeding, and reduced strength. To achieve good workability, bentonite can be added in the ratio of 2 percent to 4 percent by weight of cementitious material. The bentonite must be carefully proportioned to get the desired grout mixture. Bentonite for trial mixes must be premixed with water and allowed to hydrate for 24 hours. Preparing the bentonite in ratios of 20, 40, and 60 kg/1000 kg (44, 88, and 132 lbs/2,200 lbs) of water will give added flexibility when mixing trial batches. The bentonite should be added in small steps until the desired flowability and stability are achieved.

Once the desired physical characteristics of the fluid grout are achieved, the amount of cement needed to achieve design strength should be determined. Up to this point a 50:50 cement:flyash mix has been used. A series of mixes should be made, with the cement:flyash ratio varying from 80:20 to 50:50 in 10-percent increments. The grout should be tested for compressive strength using 50 mm (2-in) mortar cubes prepared and tested according to ASTM C109. Compressive strength at 24 hr and 28 days compared to cement content should be plotted to determine the cement content capable of providing the desired strength.

Once a backfill mix with the required physical characteristics and compressive strength is achieved, water-reducing admixtures and retarders (if necessary) can be tested for beneficial effects on the mix. Water-reducing admixture can be used to reduce water while maintaining the same workability.

A typical grout mix for annulus backfill around a precast segmental tunnel liner in soft ground is given in Table 7-1. This type of mix should provide compressive strengths in the range of 1,380 kPa (200 psi) in 24 hr and 3,450 kPa (500 psi) in 28 days.

Backfilling of steel pipes and penstocks for high-pressure water tunnels, usually associated with water supply and delivery, hydroelectric stations, and pumped storage development, are normally done with conventional concrete using admixtures to increase pumpability and flowability. The concrete is generally placed with a 125- to 150-mm (5- to 6-in) slickline located in the crown of the tunnel. Because of the need to develop full contact between the backfill concrete and the surrounding ground in pressure tunnels, contact grouting is almost always required after the concrete backfill has set and cured. Like backfill grouts designed for segmental liners, concrete backfill mixes also must be designed to remain workable for extended periods. The time from batching to placement may be up to several hours. The amount of time during which the concrete must remain pumpable and workable depends mainly on the anticipated delivery time from the point of batching to the point of placement and the time required for the actual concrete placement.

Backfill concrete mix also may need to be designed to be pumped long distances. The mix should be designed to limit heat generation during hydration and curing. The ground surrounding the placement will limit heat loss with only the limited surface area of the liner affording heat dissipation.

The concrete backfill is pumped behind the liner using a slickline, injection ports, or windows through the liner. In all but short tunnels, e.g., approximately 305 m (1,000 ft) or less, where the concrete pump can be located at the portal or shaft bottom, the backfill concrete will need to be transported through the tunnel to the pump located within the tunnel close to the point of injection. The transport of concrete to the pump location will be by rail or rubber-tired vehicle. The concrete should be agitated during transport to prevent segregation.

A typical grout mix for annular backfill around a precast segmental tunnel liner in rock is given in Table 7-2. This type of mix should provide compressive strengths in the range of 4,830 kPa (700 psi) in 24 hr and 20.6 MPa (3,000 psi) in 28 days.

A typical concrete mix for backfill around pressure pipes and penstocks in rock is given in Table 7-3. This type of mix should provide compressive strengths in the range of 4,830 kPa (700 psi) in 24 hr and 28.2 MPa (4,000 psi) in 28 days.

Concrete mix proportions and design for backfill should be performed in accordance with ACI 211, *Standard Practice Selecting Proportions for Normal, Heavyweight and Mass Concrete.*

TABLE 7-1. – THREE TYPICAL BACKFILL GROUT MIX DESIGNS FOR PRECAST SEGMENTAL CONCRETE TUNNEL LINING IN SOFT GROUND

Material	Mix 1 Quantity				Mix 2 Quantity				Mix 3 Quantity			
	1 Cu. Yd.		1 Cu. Meter		1 Cu. Yd.		1 Cu. Meter		1 Cu. Yd.		1 Cu. Meter	
Cement Type II	452	Lbs	205	kg	437	Lbs	198	kg	400	Lbs	237	kg
Fly ash Type F	452	Lbs	205	kg	357	Lbs	162	kg	400	Lbs	237	kg
Sand SSD	1,673	Lbs	759	kg	2,380	Lbs	1,080	kg	1,863	Lbs	1,105	kg
Bentonite – add as slurry	20	Lbs	9	kg	11	Lbs	5	kg	23	Lbs	14	kg
Total Water	709	Lbs	322	kg	566	Lbs	257	kg	651	Lbs	386	kg
Water Reducing Admixture									2	Oz	1	kg
Total	3,306	Lbs	1,500	kg	3,751	Lbs	1,702	kg	3,337	Lbs	1,980	kg
Grout Density	122	Pcf	1,500	kg/ m^3	140	Pcf	1,702	kg/ m^3	124	Pcf	1,980	kg/ m^3

TABLE 7-2. – TYPICAL BACKFILL GROUT MIX DESIGN FOR PRECAST SEGMENTAL CONCRETE TUNNEL LINING IN ROCK

Material	Quantity 1 Cu. Yd.	Quantity 1 Cu. Meter
Cement Type II	400Lbs	237kg
Fly ash Type F	400Lbs	237kg
Sand SSD	1,863Lbs	1,105kg
Bentonite – add as slurry	23Lbs	14kg
Total Water	651Lbs	386kg
Water Reducing Admix.	2Oz	1kg
Total	3,337Lbs	1980kg
Grout Density	124Pcf	1,980kg/m^3

TABLE 7-3. – TYPICAL BACKFILL CONVENTIONAL CONCRETE MIX DESIGN FOR PENSTOCKS AND PRESSURE-PIPES

Material	Quantity 1 Cu. Yd.	Quantity 1 Cu. Meter
Cement Type II	500Lbs	298kg
Fly ash Type F	125Lbs	74kg
Coarse Aggregate ($^3/_8$" to ½")	1,600Lbs	951kg
Fine Aggregate	1,600Lbs	951kg
Total Water	300Lbs	178kg
High Range Water Reducer to get 188 mm +/- 50 mm (7.5 inch +/- 2 inch)		
Air 4% +/- 1%		
Total	4,125Lbs	2,453kg

7.5.2 Mix Design for Cellular Concrete (Foam Grout)

Cellular concrete or foam grout is a lightweight cementitious material that contains stable air voids distributed throughout the material. Typical densities of cellular concrete can range from 480 to 1,290 kg/m^3 (30 to 80 pcf) with a corresponding 28-day compressive strength of 345 to 8,280 kPa (50 to 1,200 psi). By contrast, neat cement grout has a density in the 1,840 kg/m^3 (115 pcf) range. Cellular concrete is made by first making a neat cement grout (slurry) and then combining the neat grout with a preformed foam, where foam is first generated before being combined with the slurry. The foam has enough physical toughness and chemical resistance to the cement that it can be blended into the neat grout without significant air loss. It has the consistency of shaving cream.

The preformed foam is made from a solution that is 96 percent water and 4 percent foaming agent. The foam generally has a density in the 48 kg/m^3 (3 pcf) range. Solution ratios and densities may be more or less, depending on the manufacturer recommendations. Foam expands to usually 30 times the foam solution volume. The foaming agent must have the ability to resist the high pH environment of Portland cement-based grout. For many years, protein-based foaming agents have been made by processing animal-based proteins. A germicide is added to the foaming agent to prevent spoilage. Once the foaming agent is diluted into a solution, the germicide also is diluted so the solution has to be used within 24 hr or it will spoil. Recently, artificially produced protein foaming agents have become available which are not susceptible to spoilage.

The neat grout portion of the cellular concrete will generally have a water:cement ratio by weight in the 0.50 range. Cement/flyash mixes also can be used to make the neat grout. Flyash reduces the overall cost of the cellular concrete and reduces the heat generated during curing. The foamed grout retains the characteristics of the cement and flyash. Sand is not used with foamed grout because it would segregate and defeat the goal of having a uniform, flowable product. Type F flyash is usually favored because it is relatively inert and adds sulphate resistance. Type II cement is often used because it has a slightly slower set than Type I, and also is moderately sulphate resistant.

Because the cellular concrete is often a unique assortment of ingredients that may never have been mixed together before, a combination of analysis and trial batches is required. The preformed foam must be compatible with all the other grout ingredients. Some foaming agents have a retarding effect on Portland cement-based grout set times. The goal is to produce a cellular concrete that is as lightweight (least dense) as possible yet can meet the compressive strength requirements of the project. However, if there is substantial groundwater present, the cellular concrete also must be dense enough to displace the water. The displaced water must be given a means to be evacuated from the void being filled. This can be an open grout port or valved drain pipe through the bulkhead. Cellular concretes for tunnel backfill are usually in the 960 to 1,120 kg/m^3 (60 to 70 pcf) range. A common requirement for cellular concrete backfill is to have a 28-day strength of 3,450 kPa (500 psi).

The 28-day compressive strength will only be achieved by having the correct combination of air void content, water:cementitious ratio, and cement:flyash ratio, if flyash is used. Some cellular concrete specialty subcontractors have only a single silo for cement. In this case, the mix design process is simplified to selecting the right air void content and water:cement ratio and not considering flyash.

To perform laboratory testing, a small-batch foam generator can be used. This typically consists of a 38-l (10-gal) pressurized pot for the premixed foaming agent and water and a small foam generator. Compressed air is used to force the foaming solution out of the pot and through a foam generator, where additional air is introduced to make the foam. The foam generator is a canister filled with inert beads designed to produce turbulence (and foam) as the solution and air are forced in from one end.

When preparing trial batches, the neat grout can be mixed in a 19-l (5-gal) pail using a heavy-duty mixer of the type used to mix plastering compound. Foam can then be added and mixed into the neat grout using the same mixer. Unit weight can be easily checked with a mud balance. The mixed cellular concrete should be placed into special 4-cylinder styrofoam molds with lids typically used for lightweight grout testing. The samples should be cured for 24 hr before stripping them from the mold. Lightweight grout cylinders are fairly delicate and are stripped from the mold by carefully breaking off the styrofoam from around each sample to avoid gouging or chipping. The samples should be cured in a curing room. Grout cylinders should be tested using sulphur end-capping compound, since neoprene end caps will cause the weak cement grout to fail prematurely.

The first step in the mix design process is to hold the water:cement ratio constant and produce cellular concrete mixes that vary in unit weight by 160 kg/m^3 (10 pcf) increments for 320 kg/m^3 (20 pcf) on either side of the assumed target unit weight. A strength versus density curve will show the minimum density required to achieve the desired compressive strength. Typically, cellular concrete densities in the 960 kg/m^3 (60 pcf) range easily exceed 3,450 kPa (500 psi) in 28 days.

However, early strengths may dictate the mix design. Once the grout density is achieved, a series of cellular concrete mixes can be made that vary the water:cement ratio from 45 percent to 60 percent in 5-percent increments. Addition of water will increase the flowability of the grout but reduce compressive strength. This series of tests will show the maximum water:cement ratio allowable to meet compressive strength requirements. If the compressive strength of the cellular concrete still far exceeds requirements, flyash can be substituted for cement. The water demand of the neat grout will drop as more and more flyash is added. Water should be removed from the mix and the consistency kept constant as more flyash is added. Neat grout of cement–flyash mixes with cement replacement ratios up to 65 percent have been successfully used. The compressive strength of cellular concrete can be approximated based on the intended wet (or fresh) density, the amount of cement used, and the material age. Thus, for 28-day compressive strength, the approximation is as follows:

$$f'_c = 1.667 \text{ x } (cc)^{0.8} \text{ x } (fcd)^{1.5}$$

where

f'_c = compressive strength at age 28 days (MPa)

cc = cement content (kg/m^3)

fcd= foam concrete density (kg/m^3)

Addition of flyash will generally result in increased compressive strength values for material ages beyond 4 weeks. A good quality (e.g., high glass content–low carbon content) Type F flyash can achieve long-term strengths that are 135 to 150 percent of the 4-week compressive strength of mixes using only cement.

Table 7-4 shows a cellular concrete mix design for a 100 percent cement mix with a unit weight of 1,121 kg/m^3 (70 pcf). This sample mix design had a 28-day strength of 8,273 kPa (1,200 psi). Trial batch mix designs should always be performed with the ingredients to be used for the specific project.

Table 7-4.- CELLULAR CONCRETE MIX DESIGN
100% CEMENT AT 1121 KG/M^3 (70 PCF)
WATER:CEMENT RATIO 0.50

Material	Quantity 1 Cu. Yd.	Quantity 1 Cu. Meter
Cement Type II	1,240Lbs	735kg
Fly ash Type F	0Lbs	0kg
Water	620Lbs	367kg
Foam % vol	40%	40%
Wt	32Lbs	19Kg
Total	1892pcf	1121kg
Grout Density	70Pcf	1121kg/m3

Table 7-5 shows a cellular concrete grout mix design for a 50 percent cement–50 percent flyash mix with a unit weight of 1,121 kg/m3 (70 pcf). This sample mix design had a 28-day strength of 8,273 kPa (1,200 psi). Trial batch mix designs should always be performed with the ingredients to be used for the specific project.

Table 7-5. CELLULAR CONCRETE MIX DESIGN
50% CEMENT / 50% FLY ASH AT 1121 KG/M^3 (70 PCF)
WATER:CEMENT RATIO 0.50

Material	Quantity 1 Cu. Yd.	Quantity 1 Cu. Meter
Cement Type II	621Lbs	368kg
Fly ash Type F	621Lbs	368kg
Water	621Lbs	368kg
Foam % vol	35%	35%
Wt	28Lbs	17Kg
Total	1,891Lbs	1121kg
Grout Density	70Pcf	1121kg/m3

Table 7-6 provides typical properties for foam concrete (cellular concrete).