RECLAMATION

Managing Water in the West

Pumping Cement-Based Materials

Research and Development Office
Science and Technology Program
Final Report ST-2018-2584-02

U.S. Department of the Interior
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Research and Development Office

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Mission Statements

Protecting America's Great Outdoors and Powering Our Future

The Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.

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Pumping Cement-Based Materials

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Executive Summary

The Bureau of Reclamation is responsible for approximately 280 miles of tunnels, many of which will require repair during their expected service life. Cement-based materials are a logical and proven material for use in these repairs. Often, repairs require several workers mixing cement-based materials within the tunnel at the damaged site. The alternative to mixing at the point of repair is to pump the materials into the tunnel and directly to the placement site. This type of construction technique has been successfully used at several project sites within and outside the Bureau of Reclamation.

The scope of this report is to provide an introduction to the current understanding of pumping cement-based materials for an engineer and/or cost estimator. All information included in this document is based on published research and guides. No field or laboratory testing was performed by the Bureau of Reclamation to verify the information.

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Main Report

1 Introduction

Use of concrete pump and pipelines is a common construction technique to transport cement-based materials (e.g. normalweight concrete, neat cement, etc) from the mixing truck to the point of placement. These types of projects may require an engineer/cost estimator to consider variables such as size of pump and pipelines in addition to compressive strength, durability, and other more common design aspects. Pumps and pipelines are discussed in Sections 2 and 3, respectively.

Flow of cement-based material in the pipelines is covered in Section 4 and hydraulic models of that flow proposed by researchers is found in Section 5. Common issues of flowing concrete in pipelines is included in Section 6.

Essential to a pumping job is a "pumpable" mix. The American Concrete Institute (ACI) defines pumpability as "capability of a specific concrete mixture to be pumped through a delivery pipeline." A pumpable mix is one that is transported to the point of placement with sufficient pressure, required workability, and within a required timeframe. Several aspects of pumpable mixes are covered in Section 7.

Effects on the mix due to pumping is given in Section 8. Section 9 introduces testing devices used to measure the flow characteristics of cement-based materials.

2 Pumps

There are typically two different categories of pumps used to transport cement-based materials in pipelines. The first group is piston pumps. These can be further broken down into the type of valve. There are a variety of valve configurations, see Figure 1 and Figure 2 for two examples.

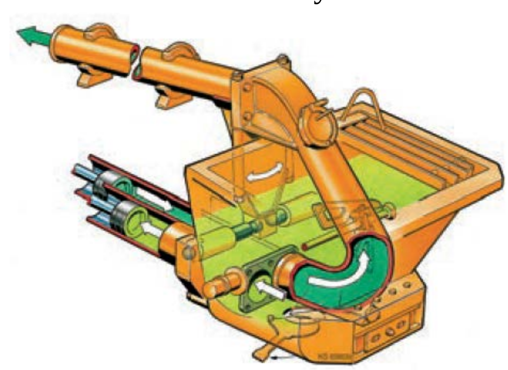

Figure 1 Piston pump with trunk valve [1].

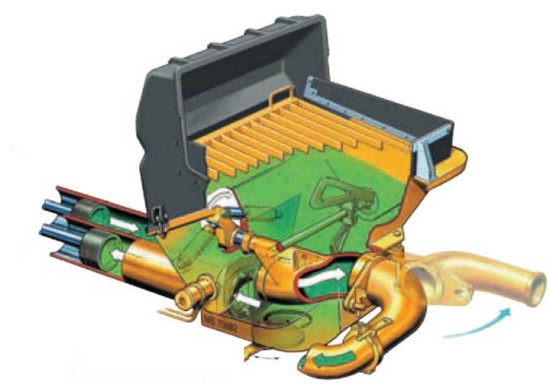

Figure 2 Piston pump with S-pipe valve [1].

Piston pumps are dual cylinder systems. One cylinder draws in the material on the intake stroke and then pushes that same material into the pipeline on the discharge stroke [2]. The second cylinder functions the same as the first but moves opposite to the first. This action produces a relatively constant flow. Many hydraulic piston pumps can be configured for piston side or rod side pumping. Piston side pumping allows for maximum pressure but with lower volumetric flow rate. Rod side indicates maximum volumetric flow rate with lower pressure. Pumps capable of this alternating configuration typically provide two flow rate vs pressure diagrams, see Figure 3. Manufactures of piston pumps for cement-based material pumping include Putzmeister, Reed, Liebher and Schwing.

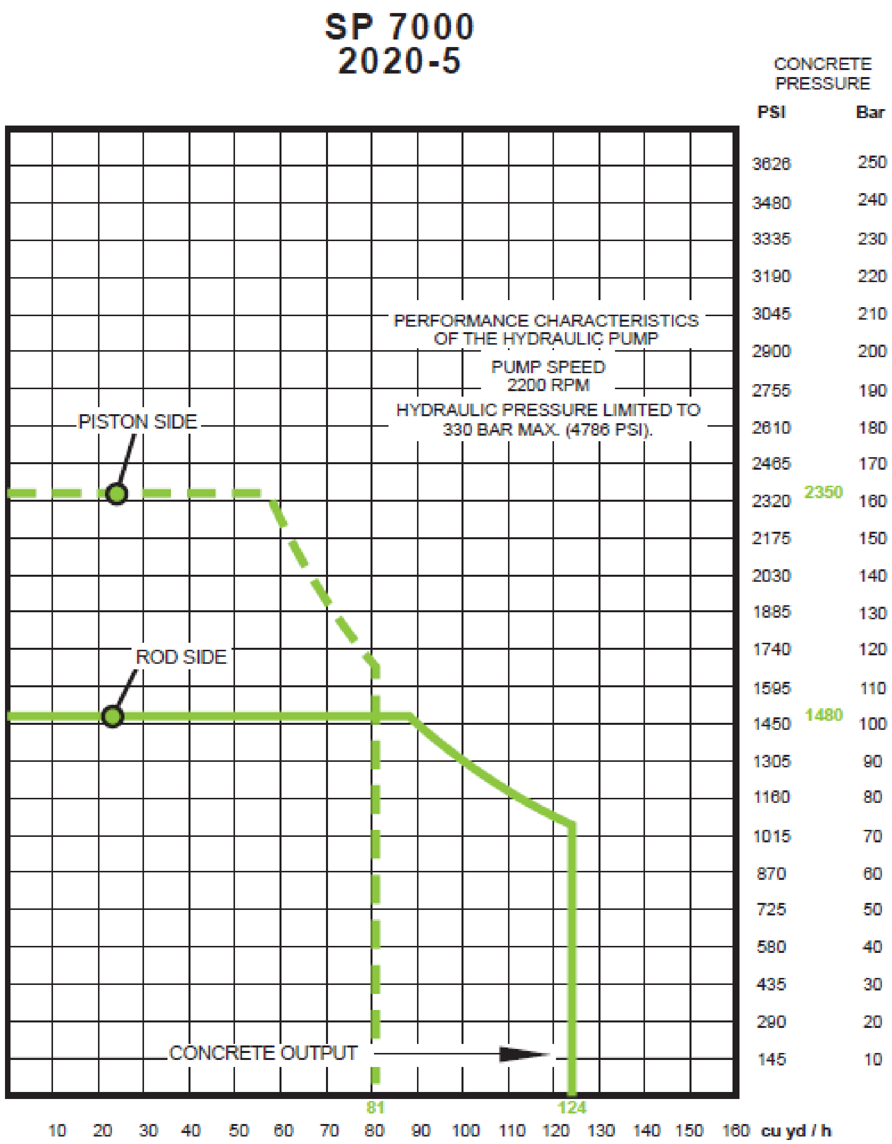

Figure 3 Performance output diagram for Schwing SP7000 pump [3]

The second group of pumps are progressive cavity, peristaltic pumps and double plunger pumps. This group of pumps typically have lower capacity in terms of volumetric flow rate and pressure when compared to piston pumps. Chemgrout is an example of a manufacturer that produces these lower capacity pumps.

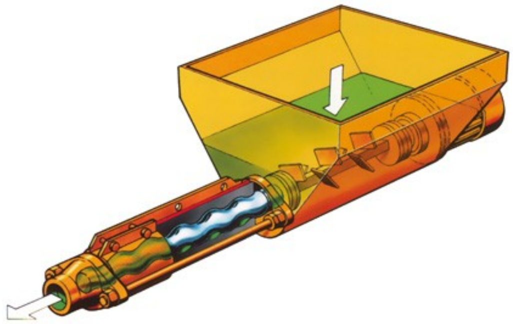

Figure 4 Progressive cavity pump (also called rotor stator pumps, "Moyno" pumps or worm pumps) [4]

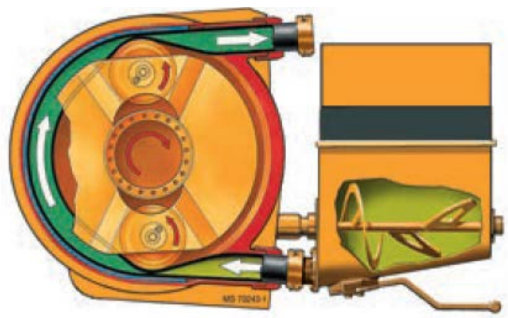

Figure 5 Peristaltic pump (also called squeeze tube pump) [1]

3 Pipelines

Pipelines for cement-based materials are usually a combination of rigid pipe, referred to as slicklines, and heavy-duty flexible hose [5]. Rigid pipe is made of steel or plastic and is available in sizes from 3 to 8 in. in diameter. Most common sizes range between 4 to 6 in. diameter.

Flexible hoses are usually made of reinforced rubber or fabric materials. The use of flexible hoses is more common at the point of placement, difficult placement areas, curves, and as connections to moving cranes [5]. Common diameter for flexible hoses are 1.5", 2", 2.5" and 3". Pumping efficiency is expected to be lower (as much as 25% reduction) with a flexible hose when compared to rigid pipe [6]. They also tend to kink or whip at higher pumping pressures [2] [5]. The whipping action could be a safety concern especially in confined spaces.

Aluminum pipeline must be avoided. Abrasion of fresh concrete on the pipe walls will erode and introduce small aluminum particles into the mix. The aluminum particles react with cement creating excessive air voids [2].

Diameter of the pipeline can have a significant impact on pumping pressures. Studies have shown that increasing the pipe diameter by 20% can reduce the pressure losses by a factor of 2 when pumping the same mix [7].

Attention needs to be given to the capacity of the pipes when estimating a pumping job, especially for longer pumping distances that will have higher than normal pressures. Standard maximum pressure rating for both rigid and flexible hoses is 1233 psi (85 bars).

4 Pipe flow

Movement of cement-based materials in a pipe occurs between two states: saturated and unsaturated [6] [8] [9]. Cement-based materials are considered saturated "when there is sufficient water in the mix to overfill the voids of the dry materials" [8]. A transition zone from unsaturated to saturated begins at a water/cement ratio (*w/c*) of approximately 0.4 for a mix with no additives [9]. The saturated state is then reached at a *w/c* of approximately 0.5 as can be seen in Figure 6.

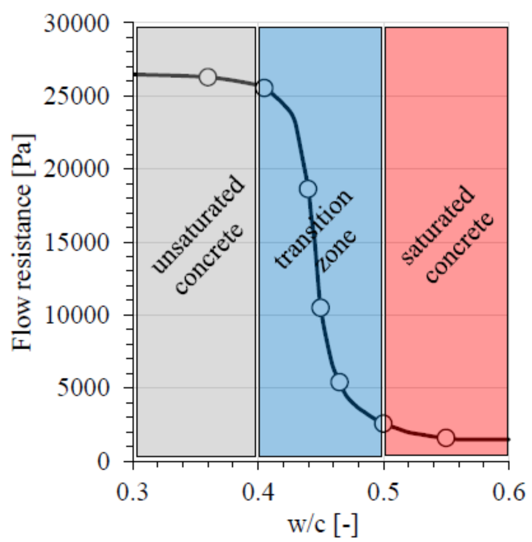

Figure 6 Frictional resistance of concrete from unsaturated to saturated state [9] [10].

Unsaturated movement is governed by friction between the fresh concrete and pipe wall [9]. It represents a "no-slip" condition and is described using Coulomb's Law of Friction for contact between two solids.

The saturated state is controlled by hydrodynamic laws. The frictional forces are negligible. The flow of concrete is unlikely to become turbulent due to its relatively high viscosity [6]. The viscosity of neat cement is lower than that of concrete and therefore has a higher potential for turbulent flow [11].

The incremental pressure loss for saturated flow is constant over the entire length of a straight pipe section and thus represents a linear relationship between pressure loss and distance. The incremental pressure loss for unsaturated movement is non-linear along the length of the pipe and results in an exponential build-up of total pressure along horizontal pipelines [9] [12]. The comparison between saturated/hydraulic flow and unsaturated/friction flow can be seen in Figure 7. It was shown that for two similar mixes, one saturated and the other unsaturated, the saturated concrete was pumped over 200 times further than the unsaturated concrete [8].

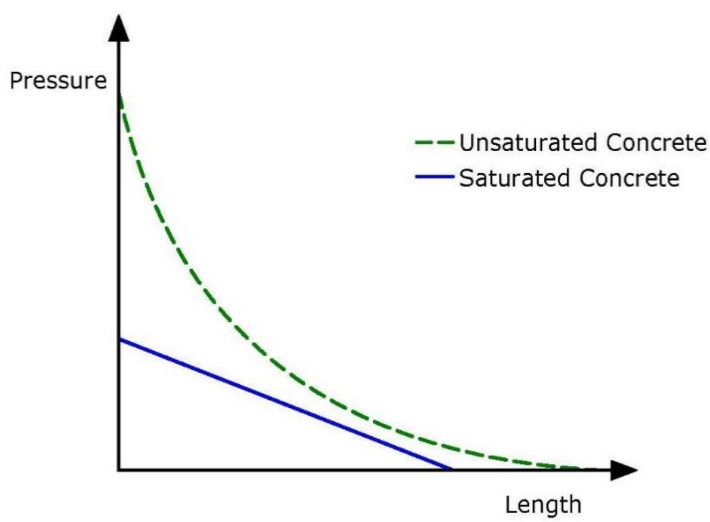

Figure 7 Schematic level graph depicting the relationship between horizontal pipe length and pressure [8].

The basic flow model for saturated cement-based materials is generally identified as a Bingham fluid (also known as Bingham plastic). The Bingham fluid itself is a type of non-Newtonian fluid. Bingham fluids have an initial yield stress that must be overcome for flow to begin. Ketchup and toothpaste are common examples used to describe Bingham fluids. The Bingham fluid is expected to flow with a linear shear stress/shear strain rate after it has reached yield. Figure 8 depicts a plot showing the relationship between shear strain rate and shear stress for both a Bingham fluid and a Newtonian fluid (e.g. water).

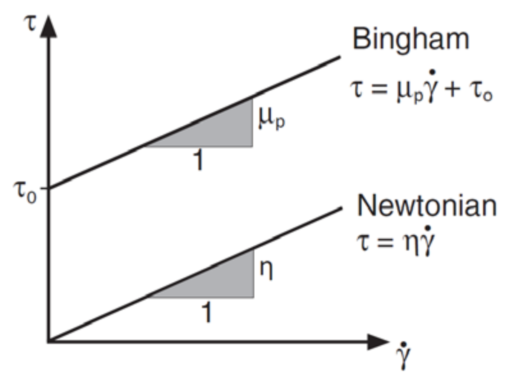

Figure 8 Bingham and Newtonian fluid comparison [13]

Figure 8 also presents the rheological properties, i.e. parameters that describe the deformation and flow of Bingham fluids. The pressure acting on the material must be large enough to exceed the shear yield stress, τ_o. The shear stress/strain rate relationship, μ_p, is assumed to be linear. The rheological properties of cement-based materials are found through laboratory testing using equipment described in Section 9. Range of values for various cement-based materials are provided in Table 1.

Table 1 Rheology of cement paste, mortar and concrete from shear tests [14]**.**

	Cement Paste, grout	Mortar	Self-compacting concrete	Conventional Concrete
Yield stress (Pa)	10-100	80-400	50-200	500-2000
Plastic viscosity (Pa-s)	0.01-1	1-3	20-100	50-100

It is understood that concrete in a saturated state flows as a plug through pipelines. This is made possible due to a lubricating layer that forms on the pipe wall. Larger particles in the mix (e.g. aggregate) tend to migrate toward the center due to shearing action from regions of higher shear stress to lower stress (i.e. from low velocity to high velocity regions). This migration forces the smaller particles and water droplets to the high shear/low velocity zone along the pipe wall and creates a lubricating layer [8] [15]. The lubricating layer consists of water, cement and fine sand particles having diameters smaller than 0.25mm [16]. Figure 9 graphically depicts this phenomenon.

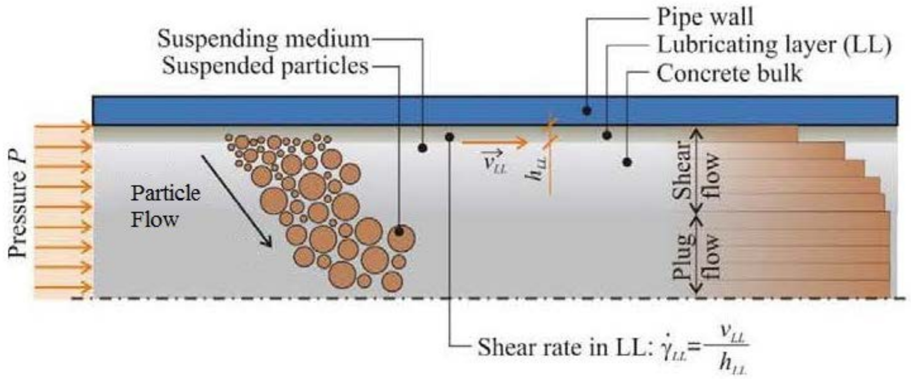

Figure 9 Particle flow of pumped concrete in a circular pipe [10].

The thickness of the lubricating layer likely depends on the composition of the mix and may also vary with the pipe diameter [17] [18] . Reports indicate its thickness is anywhere between 1 and 9mm thick [16] [18]. It is expected to increase as the volume of cement paste, *w/c* ratio and high-range water reducing admixtures increases.

A shear flow region is also likely to form between the plug and lubricating layer. It serves as a transition zone between the plug and lubricating layer and occurs at higher pressures. The profiles of each zone are shown in Figure 10.

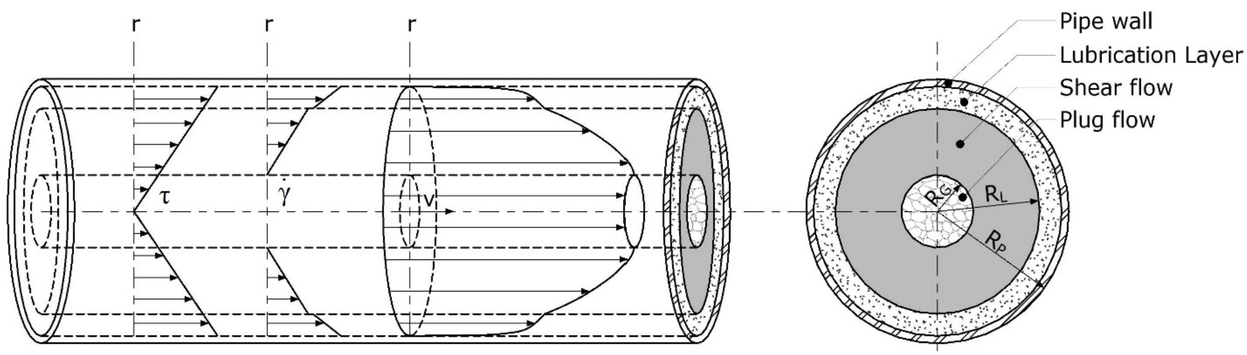

Figure 10 Flow zones with velocity, shear and shear strain rate profiles of pumped concrete in a circular pipe [12]. Note: thickness of the lubricating layer is exaggerated.

Researchers have proposed two sets of rheological properties to describe the flow of concrete in a pipe [19]. One set is associated with the interior shearing region between the plug and lubricating layer. This set consists of a yield stress and plastic viscosity for the “bulk” material. The other set is associated with the lubricating layer. It also consists of a yield stress and plastic viscosity, although at noticeably lower values.

Rheology of neat cement can be described with a single set of parameters. Namely the viscosity and yield stress of the bulk material [11].

5 Hydraulic models

5.1 Concrete

Traditionally, prediction of flow vs pressure for concrete has been done using a nomograph published by concrete pump manufacturers. These were developed based on experience with pumping the material. Conventional nomographs are limited to basic concrete mixes. That is, normal-weight concrete with cement, sand, coarse aggregate, water and little to no admixtures or supplementary cementitious materials [1] [2]. Newer nomographs have incorporated a "consistency" parameter in-lieu of the slump to provide a more robust tool. The consistency parameter is determined using pumping trials or special testing devices [1] [10]. Figure 11 depicts a generic concrete pump nomograph utilizing slump of fresh concrete.

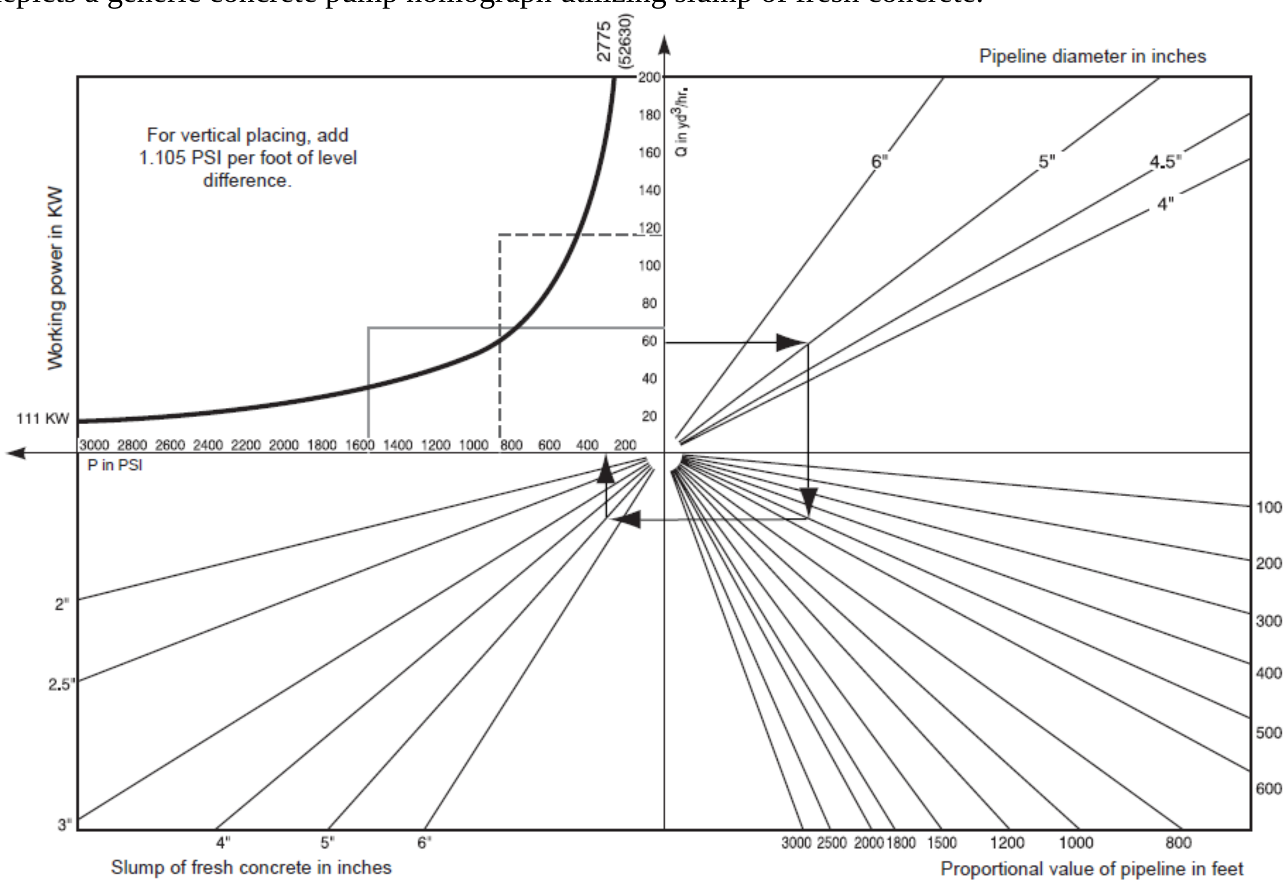

Figure 11 Example pumping nomograph for conventional concrete, from Schwing Operation Manual.

More recent work on developing hydraulic models has focused on incorporating the rheological parameters of the Bingham fluid to predict pressure/flow. These models include rheology of both the concrete/bulk material and the lubricating layer.

This report introduces the Kaplan model to estimate pressure vs volumetric flow rate for given rheological parameters [19]. Other models have been proposed in research literature, e.g. Kwon [17] and Khatib [12]. However, the Kaplan model is the most direct and has been used the longest. It presents a bilinear model where a transition occurs between plug flow and shear flow. This relationship is shown in Figure 12. Part 1 of the curve assumes the concrete flows as a full plug surrounded by the lubricating layer. This occurs at low volumetric flow rates/velocities. The bulk concrete begins to shear as the pressure increases. When the applied shear stress is greater than the bulk yield stress, viscous flow occurs at the boundary between the lubricating layer and plug [6] [19] [20]. Part 2 of the curve depicts this condition. Most of flow conditions in the pump line are expected to fall under Part 2.

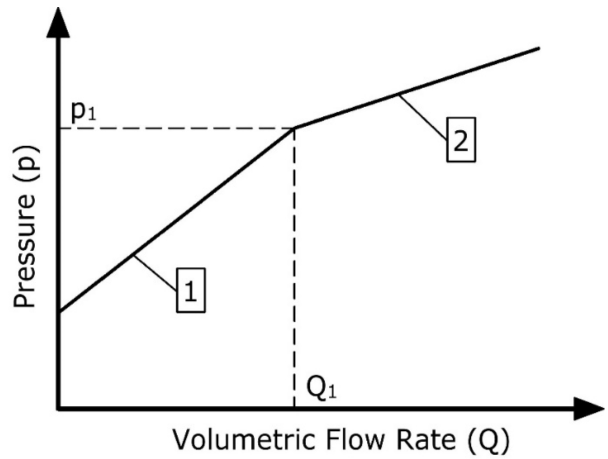

Figure 12 Graphical representation of Kaplan's bilinear model [7] [19].

Parts 1 and 2 of the curve in Figure 12 are given by equations (1) and (2) below, respectively.

$$p = \frac{2L}{R}\left(\frac{Q}{3600\pi R^2 k_r}\eta_{LL} + \tau_{LL}\right) \tag{1}$$

$$p = \frac{2L}{R}\left(\frac{\frac{Q}{3600\pi R^2 k_r}\mu_{LL} - \frac{R}{4\mu_p}\tau_{LL} + \frac{R}{3\mu_p}\tau_p}{1 + \frac{R}{4\mu_p}\eta_{LL}}\eta_{LL} + \tau_{LL}\right) \tag{2}$$

Where p is the total pressure (Pa), L is the total length (m) of the pipeline, R is the radius (m) of the pipe, Q is the volumetric flow rate of the pump (m^3/h), k_r is the filling coefficient of the pumping cylinders, τ_{LL} and τ_p are the yield stress (Pa) of the lubricating layer and bulk concrete respectively. The parameters η_{LL} and μ_p are respectively the viscous constant (Pa·s/m) of the lubricating layer and plastic viscosity (Pa·s) of the bulk concrete. The 3600 value converts the volumetric flow rate from m^3/h to m^3/s.

Equations (1) and (2) were developed setting the flow of concrete to match the output flow of the cylinder in a piston pump. Concrete material may not completely fill the volume of the cylinder as it is being drawn in. The partially filled cylinders are accounted for in the pressure loss equations (1) and (2) using the filling coefficient, k_r [15]. It is a ratio of anticipated volume of concrete in the cylinder to total volume of the cylinder. Typical values range between 0.7 and 0.9 and is closely linked to the concrete composition [20]. The more fluid mixes are expected to have a k_r of 0.9 (i.e. the paste is filling 90% of the total volume of the cylinder) while stiffer mixes will be closer to 0.7.

The relationship between the viscous constant and plastic viscosity of the lubricating layer is given in equation 3.

$$\eta_{LL} = \frac{\mu_{LL}}{e} \tag{3}$$

Where η_{LL} is the viscous constant (Pa·s/m), μ_{LL} is the plastic viscosity of the lubricating layer (Pa·s), and e is the thickness of the lubricating layer (m).

The equations for abscissa Q_1 and the ordinate p_1 defining the transition are given in equations 4 and 5 [15].

$$p_1 = \frac{2L}{R}\tau_p \tag{4}$$

$$Q_1 = \frac{3600(\tau_p - \tau_{LL})}{\eta_{LL}}\pi R^2 k_r \tag{5}$$

5.2 Cement

Pressure losses of neat cement flow in pipes is given by equation (6) for laminar flow and equation (7) for turbulent flow [11].

$$\Delta P = \frac{32L\mu_e V}{D^2} \qquad \text{for Re} < 2100 \tag{6}$$

$$\Delta P = \frac{0.1L\rho^{0.8}V^{1.8}\rho\mu_e^{0.2}}{D^{1.2}} \qquad \text{for Re} \geq 2100 \tag{7}$$

Where μ_e is an equivalent viscosity given by equations (8) and (9) for laminar and turbulent flow, respectively.

$$\mu_e = \mu_p + \frac{\tau_o}{8VD^{-1}} \qquad \text{for Re} < 2100 \tag{8}$$

$$\mu_e = \mu_p \qquad \text{for Re} \geq 2100 \tag{9}$$

Equation (10) provides the Reynolds number for Bingham fluids.

$$Re = \frac{VD\rho}{\mu_e} \tag{10}$$

An iterative procedure is needed to solve for the pressure loss. The flow is initially assumed to be either laminar or turbulent, then the equivalent viscosity is found using equation (8) or (9). The selection of flow type can now be confirmed using equation (10). If the flow type matches the initial assumption, the pressure loss can be determined using the matching Equation (6) or (7).

6 Typical issues encountered during pumping

Blockages that occur are frequently at the initial start-up and during restarts [6] [21]. A blocked pipe at start-up is likely due to accumulation of aggregate when pumping concrete. The pump strokes cause an inertia effect on the aggregate and move it slightly ahead in the mortar. Stress then transfers through friction and the material no longer moves due to the high resisting forces. The remedy is to pump a high viscosity cement paste into the pipeline before pumping the concrete to slow down the inertia of the aggregate front. It is also recommended to use low pumping rates during the initial phase to reduce the inertial effects.

A blocked pipe at restart is often due to the aggregate migrating to the bottom of the pipe [21]. This aggregate can damage the lubricating layer when it contacts the pipe wall. Flow at restart is governed by friction and requires higher forces.

Blockages that occur during normal operations are typically due to pressurized bleeding [1] [6] [12] [20] [21] [22]. This involves a transition from saturated to unsaturated during the pumping process. The pressure exerted on the concrete from the pump can push mix water past the aggregates. The space between the voids lacks mortar and the coarse particles interlock. The material becomes unsaturated leading to dissolution of the lubricating layer. Movement is now governed by friction and blockages are likely to occur.

Encrustation is another issue encountered when pumping concrete [1]. This is reported to occur at points of leakage in the pipeline. Water is pushed through the finest mortar that has settled along these points. A ring takes shape and continues to grow towards the center of the pipe. The cross-sectional area of the pipe decreases and begins to restrict the flow of material.

7 Effect of composition on pumpability

The following section presents general concepts to describe the effect on pumpability when changing parameters in the mix design.

7.1 Water to cement ratio

The *w/c* is possibly the most influential factor when pumping cement-based materials. Increasing *w/c* is expected to increase pumpability [23] [24]. There is a limit to how much water can be added to the mix before bleeding occurs. A range between 0.42 and 0.60 is the recommended starting point [23] [25]. Caution should be taken when changing the *w/c* ratio to enhance pumpability. A higher *w/c* ratio may lead to lower pumping pressures but could also reduce strength and durability of the material after it has hardened.

7.2 Cement content

Cement content promotes pumpability and provides stability to the fresh material. It is generally higher for pumped mixtures [5]. There will exist a range of cement content that a mix can be pumped. Too little cement leaves the mix prone to excessive bleeding, while too much cement results in a dry mix that is unable to provide the lubricating layer [10] [26]. A starting point for minimum cement content should be around 400 lb/yd^3 for a mix with maximum aggregate of 1 ¼" and 455 lb/yd^3 for a mix with maximum aggregate of ¾" [25].

7.3 Paste volume

Tied to the cement content and *w/c* is the paste or mortar volume. The paste volume consists of water, cementitious material, sand and air. A minimum 45% paste volume should be used as a starting point to promote pumpability [23].

7.4 Aggregate

Use of proper aggregate grading is essential for a pumpable mix. Figure 13 depicts the effect of aggregate on the rheological properties. ACI recommends a limit to the maximum size of crushed coarse aggregate to one-third the smallest inside diameter of the pump or pipeline [2]. The maximum nominal aggregate size can increase to 40% of the inside diameter of the pipe for well-rounded aggregate [5]. ACI 211.9 should be consulted for aggregate requirements [23].

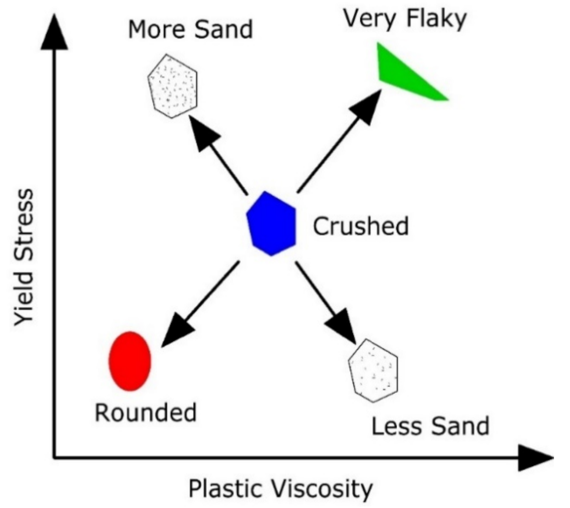

Figure 13 Effect of aggregate shape and sand content on concrete rheological properties [10] [13].

Cement, water and fine aggregates form to make the lubricating layer that transports the coarse aggregates in suspension through pump lines [5]. In general, pumpability improves with a decrease in the fineness modulus of fines, i.e. using sands with a fineness modulus between 2.40 and 3.0 [5]. Higher values of fineness modulus indicate coarser materials and lower values indicate finer materials. A disproportionately high amount of fine sand can make the mix dry leading to an increase in concrete flow resistance, similar to the excessive use of cement. The starting point for total fine content (i.e. cement and fine sand from 0 to .25 mm) should be 674 lb/yd^3 for maximum 1 ¼" aggregate and 758 lb/yd^3 for maximum ¾" aggregate [25].

7.5 Supplementary materials

The statement by ACI "Any admixture that increases workability in both normal weight and lightweight concretes will usually improve pumpability" [2] typically holds true up to a certain point. Excessive use of any supplementary materials has the potential to reduce the stability of the cement-based material during pumping. Figure 14 provides a graphical representation of the effect of various supplementary materials.

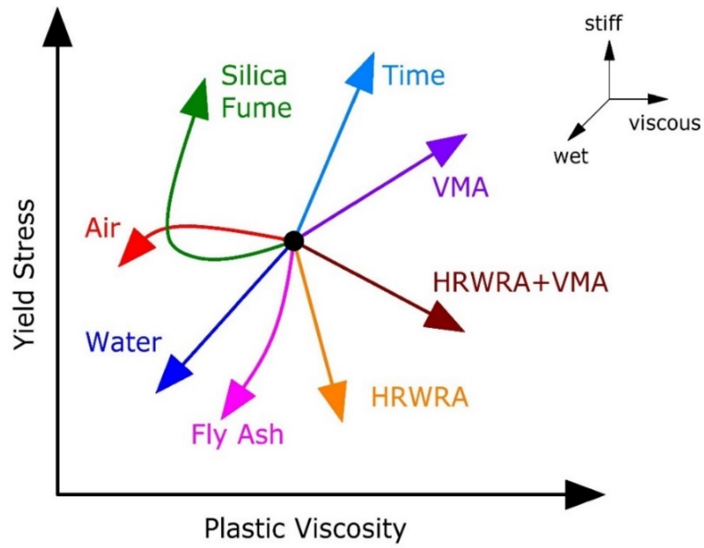

Figure 14 Effect of various supplemental materials on properties of pumped concrete [27]. The variables Water and Time are included for reference. HRWRA indicates high range water reducing admixture and VMA denotes viscosity modifying admixture.

7.5.1 Supplementary cementitious materials

Limited quantities of silica fume have shown to be effective in reducing the required pumping pressures by reducing the plastic viscosity [12]. Excess amounts will likely increase both plastic viscosity and yield stress resulting in a mix that is difficult to pump.

Replacing cement with fly ash also has the potential to lower pumping pressures [23] [28]. The optimal range for pumpability depends on *w/c* and high-range water reducing admixtures (HRWRA) dosage [12]. Class C fly ash is shown to be more effective at lowering pumping pressures than Class F due to its low HRWRA absorption rate. The low absorption rate leaves more HRWRA particles available in the mortar mix to improve the dispersing action for cement grains [12]. The allowable amount of unburned carbon in the fly ash should be kept to a minimum. Research has shown that unburned carbon reduces the effectives of the fly ash as a pumping aid [30].

It has been noted by some researchers that blast-furnace slag can increase pump efficiency [10] [23] [30]. However, other research has noted a higher potential for shear thickening behavior with the use of slag [12]. Shear thickening tends to increase viscosity when a force is applied to the fluid. This increase in viscosity is likely to reduce pump efficiency.

7.5.2 Chemical admixtures

HRWRA are known to increase concrete flowability while not requiring additional water. This increase in flowability comes at a critical dosage and depends on supplementary cementitious materials, *w/c* ratio, and polymer type [10]. Polycarboxylate HRWRA's (PCE) are most likely to be used in pumping mixes.

Including air-entraining admixtures (AEA) may also improve pumpability by increasing paste volume [12] [23]. However, the effect of the air system from pumping is discussed later and caution should be used to include (AEA) as a tool to improve pumpability.

Viscosity modifying admixtures (VMA) are typically known for increasing the stability of the mix. They are sold to “control bleeding” and “reduce segregation”. Although rheological test has shown these to increase plastic viscosity and yield stress of the concrete [13], some researchers have noted reduced pumping pressures when used in pumping tests [28].

Anti-washout admixtures (AWA) used for underwater concrete pumping improves the pumpability of concrete for distances up to approximately 150 ft [5]. Pumping pressures may increase significantly if the pumping distance exceeds 250 ft.

Essential to long distance pumping are hydration stabilizers. The intent of hydration stabilizers is to delay the cement hydration process from starting. These are more effective in pumping long distances than traditional retarders that only slow down the hydration process.

8 Effects on the mix due to pumping

8.1 Thixotropy

Thixotropy is a phenomenon where concrete in its fresh state exhibits different behavior than when it is flowing. Thixotropy involves physical attraction forces and acts on smaller particles [24]. It is defined as a “reversible, isothermal, time-dependent decrease in viscosity when a fluid is subjected to increased stress or shear rate” [31] . As shown in Figure 15, the viscosity returns to its original state when the shear stress/rate returns to its original value. The changes occur at constant temperature, thus making it isothermal. The variation in viscosity is not instantaneous and therefore considered time-dependent.

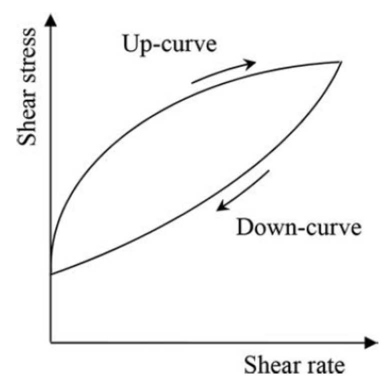

Figure 15 Thixotropic hysteresis loop [31]

It has been reported that thixotropy is noticed during high speed pumping. The fluidity of the concrete increases with higher discharge leading it more prone to loss of internal stability [31].

8.2 Structural breakdown

Where thixotropy refers to physical attraction forces, structural breakdown involves the chemical bonds created by the initial hydration [24]. These chemical bonds are broken by shearing action and take longer to build-up when compared to thixotropy. Similar to thixotropy, structural breakdown is more likely to occur at higher flow rates and longer pumping times. Unlike thixotropy, the process is irreversible [12]. The viscosity is expected to decrease because of structural breakdown. This may decrease pumping pressures but could lead to higher potential for bleeding.

8.3 Loss of air in concrete

Considerable attention has been directed towards entrained air of pumped concrete. It is believed there are three reasons why the air void system may change: suction, impact and dissolution/reappearance [32]. The total content of entrained air is expected to decrease due to pumping [5] [15].

Suction is caused when a circumstance in the placement or pump line results in the concrete sliding down a section of pipe under its own weight and thus creating a vacuum behind it. This mechanism is believed to burst larger voids but is not expected to affect the air void spacing factor.

Air loss from impact is considered solely due to placement at the end of the hose. Directing the concrete onto hard surfaces is believed to break internal air voids through mechanical impact [32]. It is assumed this type of air loss is minimized when discharged concrete is placed onto fresh concrete rather than bare ground [28].

Dissolution/reappearance describes a phenomenon when smaller air bubbles dissolve into the surrounding water when pressurized. A depressurization occurs at or near the hose exit and the previously dissolved air bubbles combine with larger air bubbles that remained in the mix [20] [32] [33]. It has been reported this mechanism is typically not noticeable at pumping pressures less than 150 psi but becomes more prevalent at pressures in excess of 300 psi. The effect also increases when fresh concrete is under pressure for extended amount of time. The time factor did not impact the void system as much the magnitude of the pressure [33]. The dissolution/ reappearance mechanism is expected to increase the spacing between air voids [20].

8.4 Temperature effects

Temperature increases in the material are expected during pumping [6] [12]. Interactions between solid particles in the mix creates friction and generates heat. An increase in temperature can increase yield stress and plastic viscosity thereby reducing workability at the point of placement. Also, the temperature increases faster at higher pressure losses. This relationship becomes more pronounced at greater pumping distances where higher pressure losses are expected.

9 Laboratory testing equipment

A rheometer measures yield stress and plastic viscosity for Bingham and other similar non-Newtonian fluids. Rheometers are typically rotational measuring devices, see Figure 16 for example. Models cited in literature are Contec BML, Schleibinger Viskomat, Tattersall Mk-III, BTRHEOM and ICAR Rheometer for concrete. Fann Viscometers are common for cement slurries.

Figure 16 Schleibinger Viscomat XL [34]

Rheometers can obtain yield stress and plastic viscosity of the bulk material. There is, as noted in previous sections, a separate set of rheological parameters affecting the concrete flow. Researchers have modified existing rheometers to obtain the yield stress and plastic viscosity of the lubricating layer. They have termed these devices tribometers. Their purpose is to determine the rheological properties at the interface between fresh concrete and steel by not allowing the concrete to shear. The BTRheom and Tattersall MK-III are two examples of rheometers that have been modified to function as tribometers [19] [35].

A relatively recent testing device for pumping concrete has been introduced called the Sliding Pipe Rheometer, “SLIPER”; see Figure 17. The SLIPER is a vertical clear plastic pipe that is separated into two sections. The top most section is filled with fresh cement-based material. The bottom section of the plastic pipe is open and the entire pipe slides over a metal piston under the weight of the material, or the material plus added weights. A sensor is located on top of the metal piston that records pressure. A distance sensor measures the speed of the sliding action. The device generates a pressure vs flow rate diagram that is used with pump performance diagrams like that previously given in Figure 11. The SLIPER can also produce a consistency parameter for use with Putzmeister pump nomographs.

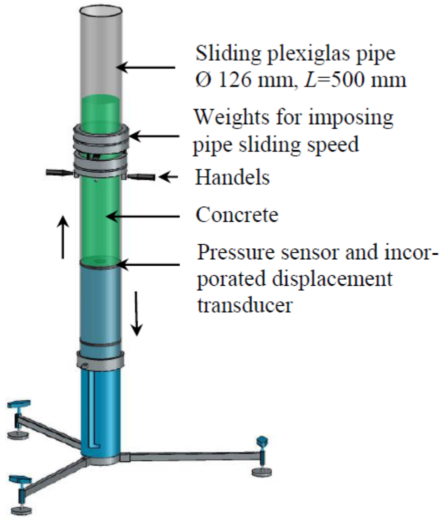

Figure 17 Sliding Pipe Rheometer (SLIPER) [10]

Recommendations for Next Steps

The report in the preceding sections introduces transporting cement-based materials using pumps and pipelines. The information is based off research articles and reports. It is recognized that restricting a research project to this type of information is beneficial up to a certain point.

Next steps to further Bureau of Reclamation general knowledge is to document actual projects that have unique challenges to pumping cement-based materials. The creation and dissemination of case studies from these types of projects, in particularly those involving long distance pumping, could be used by Bureau of Reclamation engineers and/or cost estimators to prepare designs and cost studies for similar type projects. This information could be advantageous at the early design stages (30%) to help inform the direction of the project along with its projected cost.

Complementary to this effort is to obtain laboratory data on the rheological properties of the cement-based material used in the case studies. The hydraulic models presented in Section 5 involve parameters that are acquired from laboratory testing using equipment such as those in Section 9. Utilizing these models could then broaden the applicability of the case studies to other project conditions. Furthermore, additional mix designs beyond those used in the case studies could be tested and distributed for use in preliminary designs.

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