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DEVELOPMENT OF A MOBILE HIGH SHEAR COLLOIDAL GROUT PUMP FOR THE CONSTRUCTION INDUSTRY

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Abstract

The aim of this project was to design and develop a grout pump and solve associated technical issues for a construction company in Ireland. The design is based on a high shear colloidal grout mixing and pumping rig. The initial machine has failed in terms of bearing and seal performance, has high manufacturing costs and is poorly designed.

To account for these issues, extensive research of the design features of grout mixing units from various competitors and suppliers was carried out by research and field studies at trade fairs. Using the information gathered, and incorporating improvements into the existing design, a test rig was developed and tested. Performance tests consisted of varying the flow rates of the grout material through specified industrial flow rate ranges. The head loss through the system was plotted against flow rate to obtain system design curves. Design calculations were used to size the hydraulic motor, the impeller shaft diameter, dynamic loading on bearings and their operational lifetime. The result of the performance testing indicated that the machine performance met specifications. The new colloidal mixing unit met grout mixing standards for a water/cement ratio of 0.4. This was validated with flow cone testing. The dual bearing system design proved satisfactory, with smooth operation even at higher ranges of industrial flow rates. The mechanical seals were selected for aggressive environments and the seal system developed for the grout pump remained leak proof, as designed. The original machine's mixing element has undergone a complete design overhaul, replacing the centrifugal pump with a dual bearing positive-displacement mixing mill. Machine operation was smooth and provided high quality batches of grout. The new pump design features includes a widened pumping impeller for increased shearing of the grout and gives higher volumetric flow rates. This offers enhanced mixing attributes while retaining the positive aspects of the original design such as vortex mixing, high shear colloidal mixing and portability.

Keywords: Grout pump, impellor pump, vortex mixing, grout cement

INTRODUCTION

Grout mixing involves shearing dry clumps of cement into fine individual cementitious particles. Each individual particle of cement is exposed to water, ensuring complete particle wetting. Complete wetting is necessary for batch quality. Batch ingredients and corresponding quantities are selected to meet the requirements of the grouting site. Grout mixing and pumping is the process of producing and transferring a slurry mixture of cement, sand, water and accelerating agents. This process is applied as a foundation repair solution to buildings and structures to restore structural integrity, restore damaged or failed damp courses and restrict movement of structures due to subsidence or when structural deficiencies develop in a building as a result of unexpected soil movements underneath a building's foundation. The formation of crack systems and voids in the subsoil reduces the load bearing capacity of a building's foundation, resulting in structural instability and damage. The technique involves circulating water in a vessel via a pump, adding the correct quantities of cement, sand and agents to produce a consistent paste. A vortex mixing effect is used to assist with the mixing as shown in Figure 2. This is generated by pumping the liquid tangentially into the mixing tank. The mix is then pumped to a second vessel where it is then injected under high pressure through a hose and into the location underground or for culvert repairing.

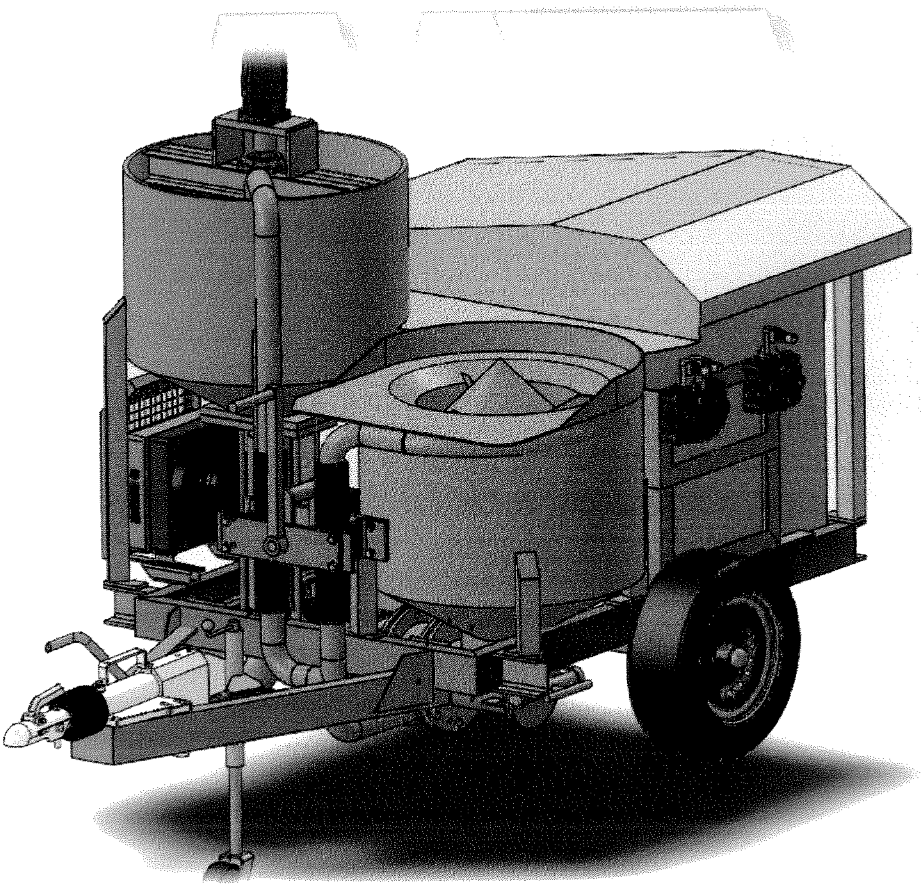


Figure 1.

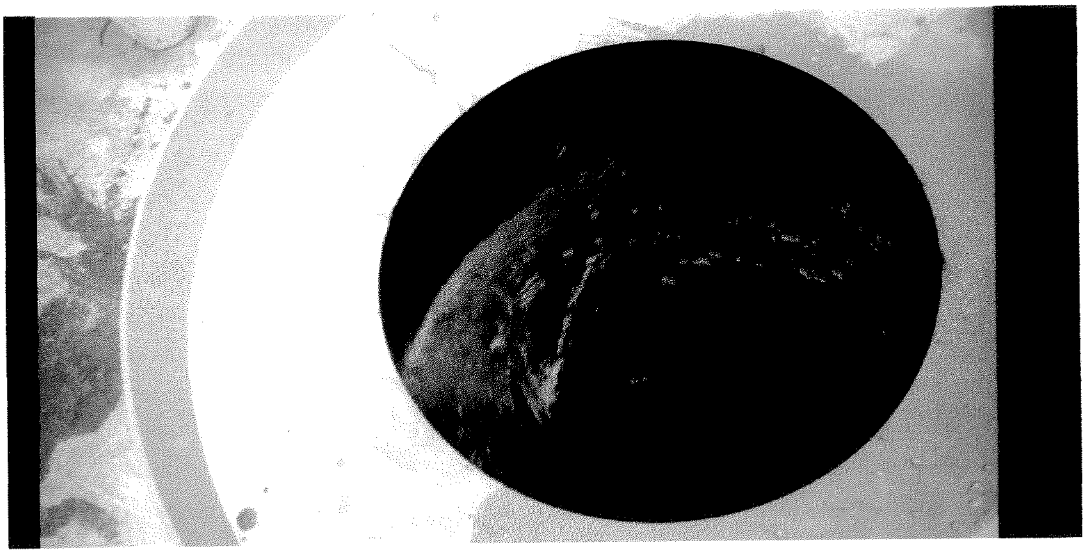


Figure 2. Vortex effect in mixing process

Figure 3. shows the drilling process in preparing the ground or foundation for the grout mix and Figure 4. shows the effect of the grout in the foundation. A mast mounted drill is used to bore holes into the structure's foundation, intercepting crack systems and voids. Freshly mixed grout is pumped into these holes, where it is then pushed into the adjacent crack systems. The grout sets to provide structural rigidity and sealing against rising damp. Upon successful grouting, structural integrity is fully restored. The foundation is capable of carrying the required loads and resisting rising damp [2].

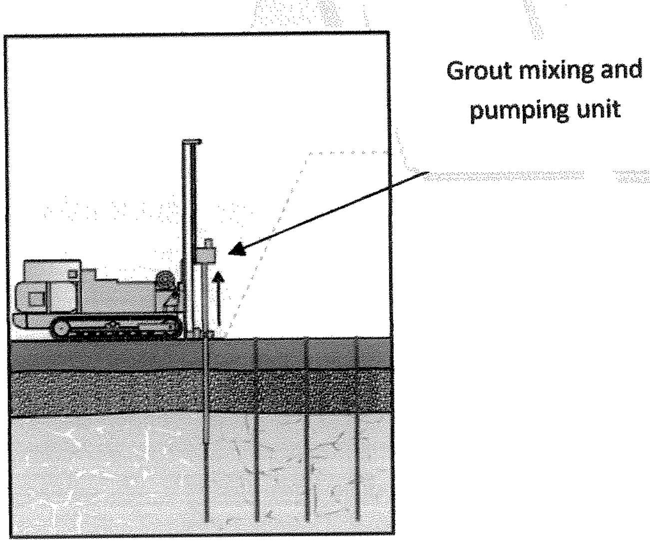


Figure 3. Schematic of Grout mixing and structural integrity fully restored [3]

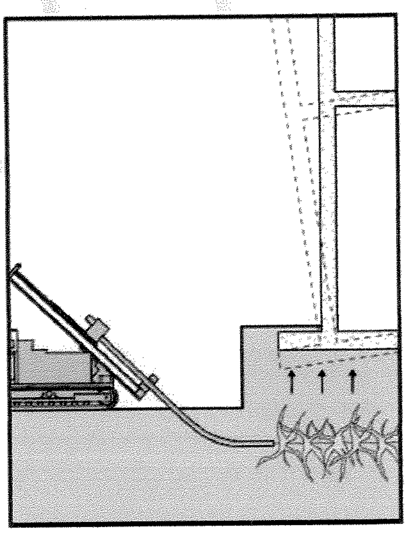


Figure 4. Successful grouting, pumping machine in operation [3]

OVERALL PROJECT AIMS AND OBJECTIVES

The main overall goals of the work were;

- To provide detailed production drawings for the existing machine
- To design and develop (with the use of the production drawings) a stationary mixing unit for testing machine performance
- To design and develop a high shear colloidal mixing pump
- To employ standard power equipment for driving the unit
    - Hydraulics
    - Diesel engine prime mover
- To provide a simple, maintenance friendly design by increasing accessibility to impeller blades
- To address bearing performance problems and seal issues
- To measure the performance and reliability of the grout mixing pump via
    - Consistency of grout
    - Performance of bearings, seals and impeller
    - Power, torque and speed characteristics for mixing
    - Plotting characteristic curves

DESIGN PROCESS

The aim of this project was to design and develop a grout pump for a Construction company, TAL Construction Ltd., Co. Cork, Ireland. The company's original design had experienced technical issues with regard to performance, reliability, ease of maintenance and manufacturability and lacked design drawing. It was confirmed by the company that the grout mixing unit had failed in terms of bearing performance, poor sealing, and high manufacturing costs. The initial pump unit was a modified centrifugal type pump, cantilevered impellor having one support bearing as shown in Figure 5. Figure 6 shows the component parts of this pump and Figure 7 shows the redesigned pump unit, supported at each end and its accessibility on the grout pump equipment.

Figure 5. Pump bearing and component parts

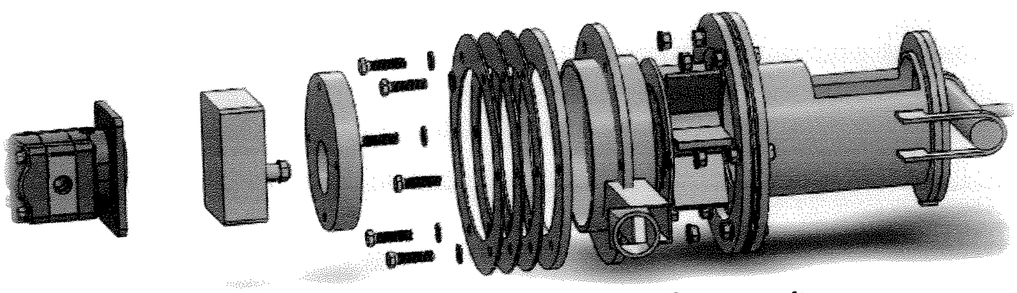
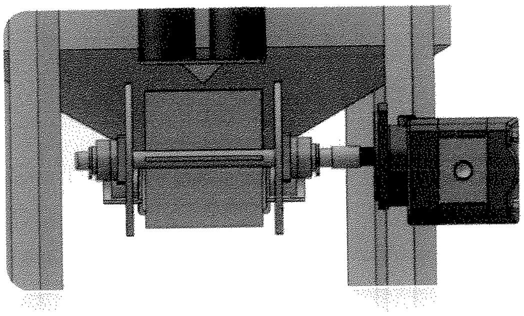


Figure 6. Exploded view of original pump unit



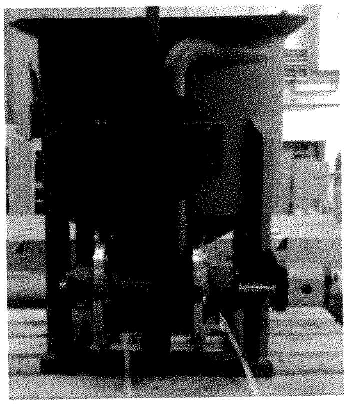


Figure 7. Redesigned pump unit and grout tank.

Design Calculations

The design of a colloidal grout mixing system depends on the required rheological properties of the end product. Referring to Figure 8., the machine must be capable of mixing grout to meet the following specifications:

- Water/cement ratio = 0.4
- Mixing time of one minute (Multiple passes through pump)
- Impeller rpm > 1500
- Thorough homogeneous mix

The grout volume, based on the size of the mixing tank is 0.155m^3
Water and cement are added to the mixing drum. For a w/c ratio of 0.4:

$$0.4 = \frac{Mass_{water}}{Mass_{cement}} \qquad (1)$$

Three bags of cement gives a total mass of 150 kgs, therefore the mass of water required is 60kg, (60 litres), generating a slurry mass of 210 kgs, giving a volume of 100 litres overall. The industry standard for recirculation flow rates in high shear colloidal mixing varies between 1000-1500 litres per minute. These flow rates are neccesary to obtain turbulent, aggresive mixing environments in the mixing unit. Testing conditions require that the machine is sized to deliver a maximum flow rate of 1500 litres/min. Therefore the entire mixing system is designed to be capable of delivering this maximum flow rate and all calculations are based this design value.

Design Flow rate = 1500 litres/min = 90 m^3/hour

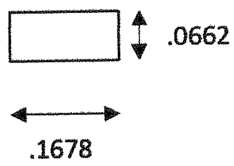
System Flow rate = Q = 90 / (60×60)=0.025 m^3/s

The entire mixing system consists of pipes/ducts and fittings of differing cross sectional areas as outlined in Figure 8. The flow rate of Q = 0.025 m^3/s remains constant through the entire system, however the grout fluid velocity varies with cross sectional area. It is therefore neccesary to compute the grout fluid velocity at each pipe segment throughout the rig.

Velocity of gout in tank

For Large diameter tanks, the velocity of the surface of the fluid can be approximated as zero.

Velocity through rectangular duct inlet/outlet



The duct inlet/outlet cross sectional area:
= 0.1678×0.0662 = 0.011 m²

$$v = \frac{Q}{A} = \frac{Q}{\frac{\pi D^2}{4}} = \frac{0.025}{\frac{\pi \times 0.095^2}{4}} = 3.52\ m\ s^{-1} \qquad (2)$$

The corresponding Reynolds Number is determined from equation (3)

$$Re = \frac{\rho v D}{\mu} = \frac{(2100)(3.52)(.095)}{0.06*} = 11704 \qquad (3)$$

Where the viscosity of the grout was determined to be 0.06 Pa.s (Marsh funnel) [4].

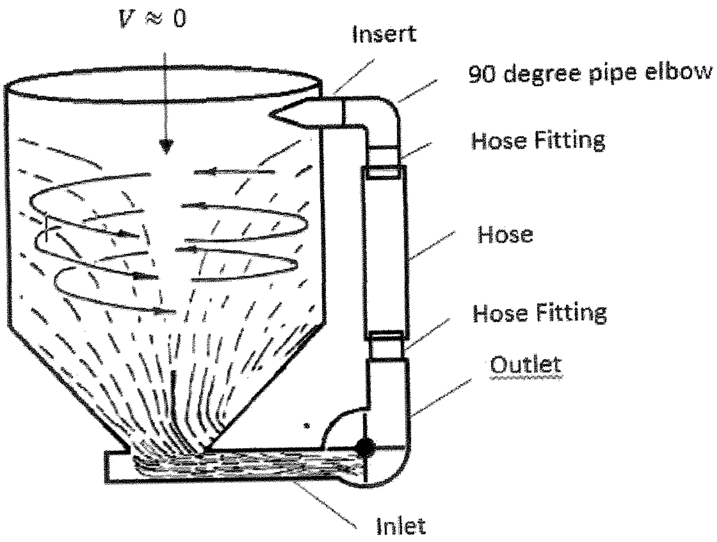


Figure 8. Schematic of mixing tank with variable cross sections

Head Losses in system

Equation (4) is the Steady flow energy equation for the system [3]:

$$h_{pump} = \frac{p_2 - p_1}{\rho g} + \frac{\alpha_2 V_2^2 - \alpha_1 V_1^2}{2g} + (z_2 - z_1) + h_{losses} \quad [5] \qquad (4)$$

Since the holding tank and the mixing tank are open to atmospheric pressure, the pressure difference is zero. There is no elevation difference between the mixing tank and the holding tank, therefore
$(z_2 - z_1) = 0$ and equation (4) reduces to equation (5)

$$h_{pump} = \frac{\alpha_2 V_2^2 - \alpha_1 V_1^2}{2g} + h_{losses} \quad (5)$$

and assuming that V_1 and V_2 are approximately zero for a large diameter reservoirs; therefore

$$h_{pump} = h_{losses}$$

and the losses are given by the following Darcy/Weisbach equation

$$h_{losses} = h_{loss_{major}} + h_{loss_{minor}} = f\frac{L}{D}\frac{V^2}{2g} + \sum K\frac{V^2}{2g} \quad (6)$$

Therefore the Head required by the pump unit is given by equation (7).

$$h_{pump} = f\frac{L}{D}\frac{V^2}{2g} + \sum K\frac{V^2}{2g} \quad (7)$$

Figure 9. shows a schematic of the mixing tank and holding tank of the system.

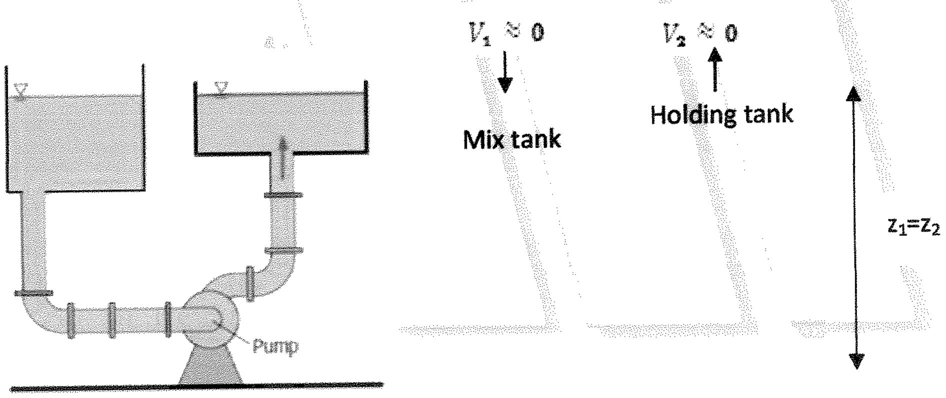


Figure 9. Illustrative image of grout mixing and pumping system [7]

Table 1. Shows the results of the major losses through the system including all pipes, ducts and fittings.

Table 1. Major losses in system

Component	Relative Roughness	Length (m)	Hydraulic Diameter (m)	f_{moody} (Friction factor)	Reynolds Number	Velocity (m/s)	h_f (m) $\left(f\frac{L}{D}\frac{V^2}{2g}\right)$
Main tank	-	-	-	-	-	-	-
Inlet Duct	0.000526	0.365	0.095	0.032	11704	3.51	0.077
Outlet Duct	0.000526	0.07	0.095	0.032	11704	3.51	0.0148
Hose fitting	0.00607	0.046	0.0428	0.035	26017	17.36	0.577
Rubber Pinch hose	0.000147	0.282	0.068	0.0285	16374	6.88	0.285
Pipe elbow (90°)	0.00607	0.116	0.0428	0.035	26017	17.39	1.45
Insert pipe	0.00607	0.228	0.0428	0.035	26017	17.36	2.85

The total head loss, H_t through the entire system is the sum of the losses column as shown in equation (8)

$$H_t = .077 + .0148 + .577 + .285 + 1.45 + 2.85 = 5.25\ m \quad (8)$$

Minor Head losses

Loses due to bends, enlargements, entrances and exits are accounted for by the summation for all the loss coefficients (K values) of the system as shown in Figure 10.

$$K_T = K_{divert\ entrance} + K_{connection\ exit} + K_{connnection\ entrance} + K_{bend} + K_{insert\ exit} \quad (9)$$

The sum total of the loss coefficients is multiplied by the average velocity of the system. The average velocity depends on pipe lengths and varying cross sectional areas and therefore must be calculated by the weighted average velocity method, giving a value of 10.67 m/s.

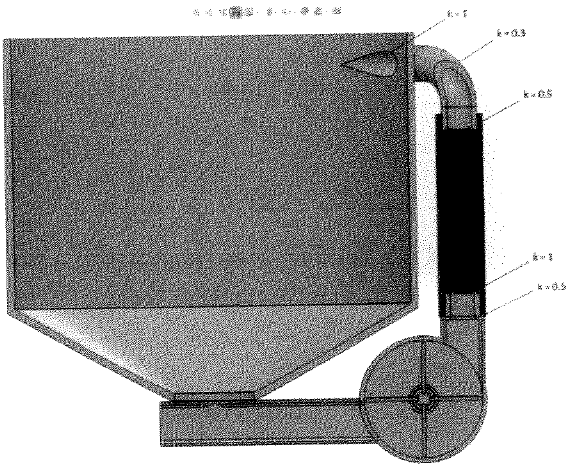


Figure 10. Head loss coefficients

The total k coefficient is the sum of these values outlined in Figure 10.

$K_t = \Sigma\,(.5 + 1 + .5 + .3 + 1) = 3.3$

and from the Darcy-Weisbach equation

$$\sum_{All\ ducts} f\frac{L}{D}\frac{V^2}{2g} + \sum K\frac{V_a^2}{2g} \quad , \quad \text{and} \quad V_a = 10.67\ m\ s^{-1}$$

Therefore

$$h_l = 5.25 + \frac{(3.3)(10.67)^2}{(2)(9.81)} \quad , \quad \text{giving } h_l = 24.39\ m$$

$$Power = \rho g h_t Q$$

$$Power = (2100)(9.81)(24.39)(.025) = 12561.4\ W = 12.56\ kW$$

Where g = 9.81m/s², h_t is the total head losses, Q is the flow rate and ρ the fluid density.

Therefore the design power required for the Grout pump for the mixing and pumping unit is 12.56 kW

CONCLUSIONS AND KEY DESIGN IMPROVEMENTS

The aim of this project was to improve the technical performance associated with a grout pump and mixing rig. To achieve this, a number of key objectives were addressed;

1. **To provide detailed production drawings for the existing machine**
   Sketches were produced on site and these generated 3D CAD models and 2D manufacturing drawings. Standard parts were identified and selected from design calculations.

2. **To design and develop a stationary mixing unit for testing machine performance**
   A concept design for the test rig was developed. This featured the original centrifugal pump unit connected to the mixing drum. A new design for the mixing impellor was designed and developed and manufactured to specification.

3. **To design and develop a high shear colloidal mixing pump**
   The new design utilizes a twin bearing, positive displacement mixing unit with a widened impeller to provide increased shearing area and higher volume flow rates. The widened impeller is one of the key features of the mixing unit. It accounts for increased shearing area, and therefore more cement particles are wetted. In addition, the wider impeller displaces more volume per revolution, therefore increasing flow rates. Vortex formation is enhanced which improves mixing, wetting and turbulent flow in the mix. As a mixing unit, this new design has improved reliability, enhanced mixing capacity (due to high shearing area) and employs a better sealing system to cope with aggressive environments as shown in Figure 11.

4. **To provide a design for maintenance and accessibility**
   With the new design, the time taken for maintenance has been reduced from 1 day to 30 minutes. This is due to the simplified design of the new mixing unit. With only a flange to remove from the mill, access to the blades is immediate.

5. **To improve bearing performance problems and seal issues**
   The original machine suffered bearing failure as a result of a cantilevered impeller. Deflection of the impeller translated into additional dynamic loading on bearings, resulting in premature bearing fatigue and failure. This problem was solved with the use of a dual bearing system and eliminating the cantilever effect. The calculated value of dynamic loads on the bearings was found to be 5.41 kN which is well under the rated value of 14.6 kN [6]. The seal included a Tungsten Carbide shaft seal which was designed for abrasive environments.

6. The results of mixing was positive with a thourough homogenous mix obtained for a w/c ratio of 0.4 for grout. No leaks or part failure was observed. The power required to drive the impeller for mixing was calculated to be 12.56 kW. The overall torque on the impeller was calculated to be 66.63 Nm. The system was sized to cope with the highest industry standard flow rate of 1500 litres/min.

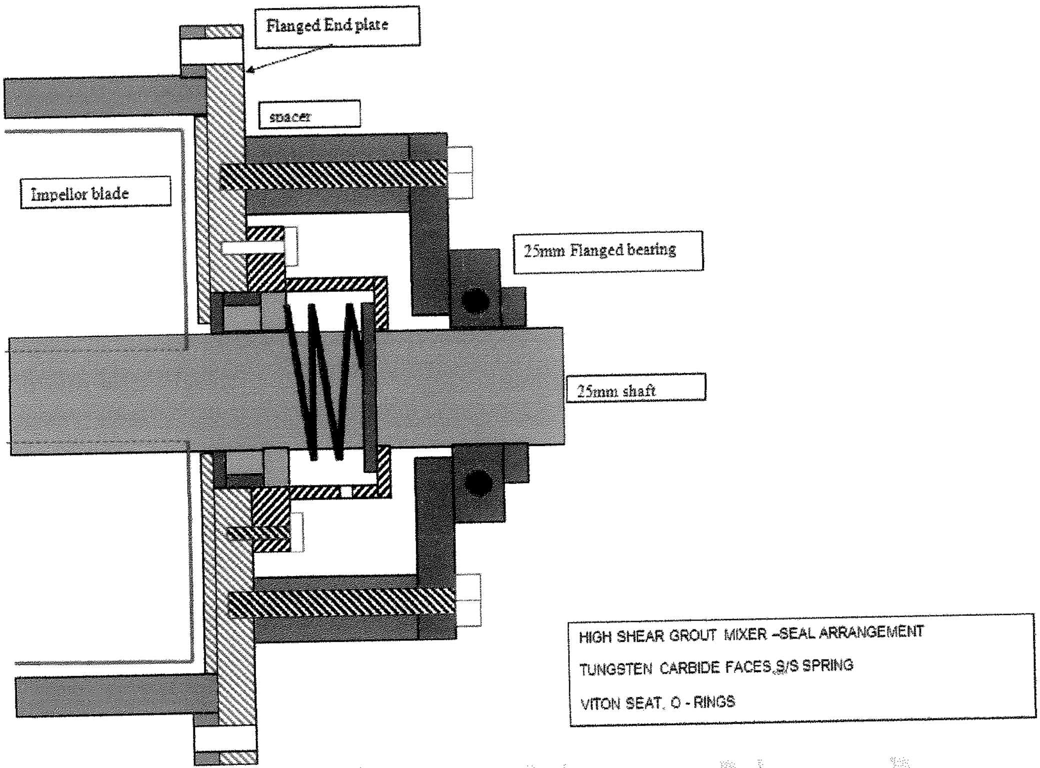


Figure 11. Bearing and seal system for grout pump.

A side and elevation view of the tank, mixing unit, hydraulic motor and support frame are shown in Figure 12a) and 12b).

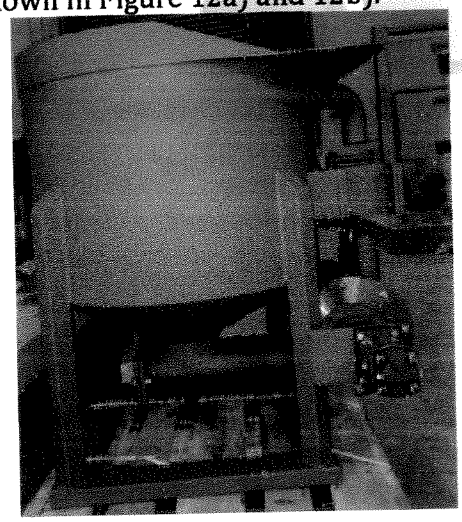


Figure 12 a) Side view of grout rig

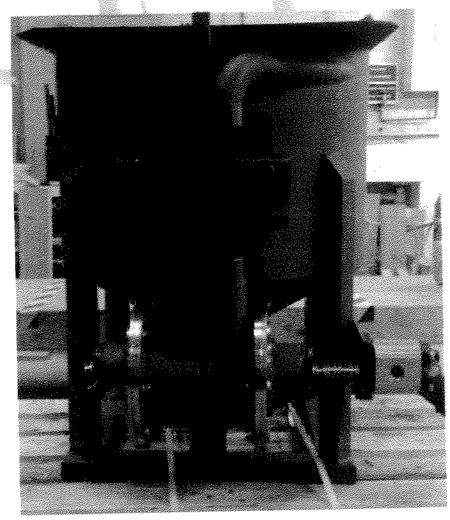


Figure12 b) Front elevation of grout rig.

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