Rheology of grout for preplaced aggregate concrete. Investigation on the effect of different materials on the rheology of Portland cement based grouts and their role in the production of preplaced aggregate concrete.

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Rheology of Grout for Preplaced Aggregate Concrete

Investigation on the effect of different materials on the rheology of Portland cement based grouts and their role in the production of preplaced aggregate concrete.

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Rheology, grout, preplaced aggregate concrete, superplasticizers pulverised fuel ash, yield stress, plastic viscosity, flexure strength, compressive strength, sorptivity and grout injection.

Abstract

Preplaced aggregate concrete (PAC) is produced by grouting high workability cement based grouts among the voids of compacted coarse aggregate mass. Because of its low shrinkage, PAC has been used for many repair jobs like; tunnel lines, dams and bridge piers. Moreover, it has been used for underwater construction.

Grout has a major effect on the properties of produced PAC and well defined grout controls the properties of resulted PAC. The effect of types and amount of powder materials, admixtures, sand and water content on the properties of fresh and hardened grout for the production of PAC have been investigated. Tests on hardened grout and PAC properties have also been carried out to investigate the most important effects. A correlation between hardened properties of grout and PAC has also been analyzed.

Grout rheology using four different gradation sands at two different cement-sand and at different w/c ratios ratios has been identified experimentally; no added chemical admixtures or mineral additives had first employed, then superplasticizer (SP) was added at 2% and 1%, and finally a combination of 1% SP and pulverized fuel ash (Pfa) at 20% of the cement weight was employed for all mixes. Grout tests have included two point workability tests by the Viskomat NT, flow time funnel test, Colcrete flow meter test, and water bleeding test. After that, eighteen grout mixes with high workability were produced using three different sands at three w/c ratios and two c/s ratios with 1% SP and Pfa at 20% of the cement weight were designed. Eighteen hardened grout and PAC then produced and their compressive strength and sorptivity were tested.

Grout rheology can be defined by the rheology of cement paste employed and the internal distance between sand particles. The effect of sand surface texture on grout rheology is important at very low internal distances. Fresh grout yield stress is the most important property which gives the same degree of sensitivity for all grouts regardless the material type and content used in the mix. There are strong relations between compressive strength of grout and PAC, but less correlation between them in sorptivity test because of the effect high quantity of coarse aggregate of PAC. Sorptivity of PAC is low comparing with different kinds of concrete suggesting its advantage for underwater construction.

To my father

For his sacrifices;

He left his successful study

and started working at early age

to save the whole

family

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Abbreviations

All symbols are used as defined below unless they are defined immediately after being used in the text.

PAC	preplaced aggregate concrete
SP	superplasticizers
Pfa	pulverized fuel ash
W/c	water-cement ratio
C/s	cement-sand ratio
b_0, b_1, b_3, b_4, b_5, $b_6$and b_7	fluidity regression coefficients presented by Abdelgader (1995and 1999)
f_g	grout compressive strength
α_0, α_1, α_2 and α_3	grout compressive strength regression coefficients presented by Abdelgader (1995 and 1999)
NC	normal concrete placement method
w	weight of water C, weight of cement
S	weight of sand
ρ_c	specific gravity of cement
ρ_s	specific gravity of sand
e	void ratio of compacted coarse aggregate
f_c'	compressive strength of preplaced aggregate concrete
$\gamma_0, \gamma_1, \gamma_2$ and γ_0 ,	PAC compressive strength regression constants presented by Abdelgader (1995 and 1999)
$\beta_0, \beta_1, \beta_2$	regression analysis constants for the relation between grout and PAC compressive strength presented by Abdelgader (1995 and 1999)
f_{tp}	tensile strength of preplaced aggregate concrete
E	modulus of elasticity of PAC
τ_0	yield stress

τ	shear stress
η	plastic viscosity
$\nu^{\cdot}$	shear rate
η_∞	viscosity at very high shear rate
A,B,C	rheological constants.
T	torque registered by the Viskomat NT
N	rotation speed of the Viskomat NT
g	yield stress parameter
h	plastic viscosity parameter
C_3A and C_3S	cement minerals
d	relative reactivity of cement minerals
AEA	air entraining agent
HRWRA	high rate water reducing admixtures
SCC	self compacting concrete
ggbs	ground granulated blast furnace slag
η_r	relative viscosity of grout to cement paste
t_p	excess paste thickness between aggregate particles
μ	fineness of sand
v	volumetric concentration of sand
c	solid volume ratio of sand
η_{rc}	concrete/mortar relative viscosity
τ_{yr}	concrete /mortar relative yield stress
Γ	excess mortar thickness between coarse aggregate particles in concrete
S1, S2, S3 and S4	are sand types
SSD	saturated surface dry
OD	oven dry
$w1$	weight of the pycnometer filled with water.

$w2$	weight of the pycnpmeter filled with 800 gm sand and topped with water
V	void ratio of sand
γ	aerated sand density
SG	specific gravity of sand
G/C	grout/concrete weight ratio
i	the increase in sample weight in sorptivity test
S_g	sorptivity of grout
S_c	sorptivity of PAC
T	measured time in minutes at which the mass is measured during sorptivity test
f_t	flexure strength of grout
f_{cu}	compressive strength of cubic PAC samples
C/G	concrete/grout strength or sorptivity ratio

CHAPTER 1: INTRODUCTION

1.1 General

Preplaced aggregate concrete (PAC) is a two stage technique of concrete production; in the first stage, coarse aggregate is compacted in the forms to be concreted then, the remaining voids between coarse aggregate particles are filled by grout under pressure in the second stage. Coarse aggregate volume occupies about 65 to 70 % of the volume of concrete. Grout usually contains cement, fine sand, pozzolans and other pumpability agents (Mehta, 1986; and Neville, 1995).

The drying shrinkage and permeability of PAC are less compared with those of conventional concrete due to the point to point contact of coarse aggregate particles without any clearance for the cement paste. Consequently, PAC is suitable for construction of water-retaining and large monolithic structures and for concrete repair works. Due to the method of placement, as the coarse and fine aggregates are placed separately, the worry of segregation of heavy coarse aggregate is eliminated which makes this method suitable for high density concrete structures, such as nuclear shields and for underwater construction (Warner, 2004; and Neville, 1995).

Preplaced aggregate concrete has been used for many repair jobs such as, tunnel lines, dams and bridge piers; it has also been used for underwater construction (Davis, 1960; Troxell, 1969; Baumann, 1948; Davis et al., 1956; and ACI 304.1R, 1997). The method has been used in different countries under different names like; Preplaced aggregate concrete in the USA, Colcrete in the UK, Polcrete in Poland, Two stages concrete, Intrusion concrete, Grouted concrete and Pre-packed concrete (Littlejohn, 1984; Davis, 1960; and Abdelgader, 1995).

PAC has a wide use for underwater construction because of its suitability to cast concrete underwater. First, the coarse aggregate is put into the form then, water is displaced by the grout during the injection process. For underwater concreting, PAC should have a high water tightness to protect the reinforcement steel, and hence, investigation of water penetration in PAC is very important. Since, water tightness can be achieved by eliminating the continuity of pores within the concrete mass, then the sorptivity test is useful to investigate concrete absorption.

1.2 Aims and objectives of the study

Properties of grout for preplaced aggregate concrete are very important because coarse aggregate is not involved in the mixing process to produce this concrete. Grout must develop good strength and durability and be of course highly penetrable with low shrinkage and bleed (Warner, 2004). Consequently, the choice of grout ingredients is critical to achieve the required properties. In addition, grout quality needs to be proven through laboratory tests in order to confirm its suitability to fulfill the intended purposes. Grout workability for PAC is now measured only by the flow cone test presented by ASTM C939, which was developed a long time ago.

The aim of this research is to investigate the effect of different materials on the fresh properties of grout and their role in the production PAC. Grout materials are water content, sand type and content, mineral additives like pulverized fly ash and chemical admixtures such as superplasticizers. There is also a need to evaluate other laboratory tests than the flow cone which has some limits (Roussel and Roy, 2004), like rheological properties which measure grout yield stress and plastic viscosity and gives a better description for the grout. Studying different factors affecting fresh grout properties and relating that to the hardened grout will lead to a better understanding and control of the quality of produced PAC.

The objectives of this research are summarized below:

-To study the effect of water content, sand gradation and content on the grout rheology.

- To study the effect of superplasticizer (SP) and pulverized fuel ash (Pfa) and their combination on the fresh and hardened grout properties.

-To investigate the relation between fresh grout properties and the penetration process through a compacted coarse aggregate mass in order to produce PAC.

-To investigate the effect of fresh and hardened grout properties on the compressive strength and sorptivity of PAC.

-To investigate the relation between compressive strength and water sorptivity of PAC in order to optimize its durability.

1.3 Research Strategy

To achieve the above objectives, the research strategy approach has been employed as follow.

An experimental program has been carried out in the lab on four different sand gradations with maximum size of 2mm. Sand physical properties are first investigated. Cement paste rheology was then measured by the Viskomat NT at different w/c ratios.

Cement-sand grout rheology was also measured at different w/c and c/s ratios. The effects of different mix proportions on the relative grout-paste rheological performance are then presented. A total number of 40 mixes were investigated in this part; rheology of 7 of them was not measured because they were too stiff for the Viskomat to function correctly.

Effect of different grout mix proportions on the resulting grout rheology and concrete production were then investigated experimentally. Grout was first produced at different water-cement (w/c) and cement-sand (c/s) ratios using different sands, their rheology and bleeding were measured, and then grout was injected at 2m head by plastic pipes into a coarse aggregate mass of 150mm cubic moulds. Rheology of fully injected grouts was recorded and the threshold of the injection process then identified.

From the injection process, it was noticed that grout needs a high water content to fulfill the injection process. But because the high water content will adversely affect on the properties of PAC, it was decided to employ SP at 2% for all mixes and using lower w/c ratios at the same c/s ratios using different sands. Rheology and bleeding of grout mixes was then measured and the effect of these materials in improving the injection process was investigated. After that, the same work was repeated by employing 1% of SP for all mixes because of high segregation and bleeding resulted from 2% SP.

Due to the segregation of some grouts especially those of low sand contents at SP of 1% percentage and the advantages of employing Pfa in PAC production, it was decided to investigate the effect of 1% of SP with 20% of cement by weight replaced with Pfa. The influence of rheology of grout mixes on the penetration through the coarse aggregate was identified.

By employing 1% of SP and Pfa at 20% better results were obtained with full injection and very low bleeding. The grout consistency required to complete penetration through the coarse aggregate was also identified by rheology tests, flow cone test and Colcrete flow meter test. Consequently, it was decided to employ these materials in the production of PAC. After that, eighteen grout mix proportions were chosen to produce concrete; three w/c ratios and two c/s ratios using three different sand gradations.

Finally, eighteen grout mixes were produced, their fresh properties were measured. Hardened grout was also produced and their flexure, compressive strengths and sorptivity were measured at 28 days. PAC was also produced by injecting the eighteen grouts into coarse aggregate mass of 150 mm cubes and their compressive strength and sorptivity were also measured at 28 days. The effect of different materials on fresh grout, hardened grout and concrete were investigated. Relations between hardened grout properties and PAC properties were also correlated.

1.4 Thesis layout

This thesis is divided into eight chapters as briefly explained below. This chapter gives a brief background to the preplaced aggregate concrete method, its importance in concrete construction, the role of grout on the resulting concrete properties and the objectives of the present investigation.

The second chapter illustrates the literature review of the published work on PAC. It presents the production, advantages and disadvantages of the method, and properties of

PAC. Moreover, a review covering grout production and fresh consistency and available measuring devices is also presented with a relevant background to the rheology of paste and grout used in other applications. The literature review ends with some conclusions.

The third chapter investigates the rheology of cement paste and cement-sand grout. The effect of different water-cement (w/c) and cement-sand (c/s) ratios using different sand types on the rheology of cement based grouts is investigated. An experimental investigation on sand physical properties in terms of excess paste thickness and their effect on the relative performance of grout-paste rheology are presented.

In chapter four, the effect of different w/c and c/s ratios on the rheology of grout is investigated using different sand gradations with and without superplasticizer (SP) and pulverized fuel ash (Pfa) in the mix. Neither SP nor Pfa was used in the the first stage. After that, SP was employed as a chemical admixture at 1% and 2% for all mixes. Finally pulverized fly ash as a mineral additive was used at 20% as a replacement of cement by weight with 1% SP for all mixes.

Chapter five investigates the inject-ability of all grouts presented in chapter four through the coarse aggregate to produce PAC. Moreover, a suitable combination of SP and Pfa in grout injection was investigated. The required grout injection rheology threshold to produce PAC was identified. From the combination of SP and Pfa as presented in the final stage, eighteen mixes with full penetration among the voids of coarse aggregate and low bleeding were then chosen to produce PAC. Three sand types, three w/c ratios and two c/s ratio were employed.

Chapter six deals with only eighteen grouts; their fresh and hardened properties are investigated. The first part investigates the relations between different factors on fresh grout rheology and bleeding. The second part presents the relationships between fresh grout rheology and hardened grout properties. Finally, the last section shows a correlation between different properties of the grout in its solid state such as flexure, compressive strengths and sorptivity.

In chapter seven, eighteen PAC mixes were produced by grouts presented in chapter six and the effects of w/c and c/s ratios on the compressive strength and sorptivity of PAC are presented. In this chapter also, a correlation between hardened grout and PAC is shown to study the possibility of prediction of PAC properties from small scale testing on grout.

Finally, chapter eight gives a brief summary and the major conclusions of the study together with some suggestions for future work are presented.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Preplaced aggregate concrete (PAC) is a low volume change concrete due to the point to point contact between coarse aggregate particles. PAC drying shrinkage is about one-half of that resulting from conventional concrete (Dension and Harold, 1991; ACI 304.1R, 1997) which makes it more suitable for repair works. By employing preplaced aggregate concrete, different underwater concrete structures have been built for instance, bridge piers, dams and offshore structures (ACI 304.1R, 1997; Troxell et al., 1969; and Domone and Jefferis, 1994).

PAC can be used in massive concrete construction where temperature rise must be controlled. Coarse aggregate can be cooled by circulating cold water around the particles where this water will be replaced by the injected grout. On the other hand, in cold weather the coarse aggregate can be preheated by circulating steam around it (Neville, 1995; and ACI 304.1R, 1997).

Preplaced aggregate concrete contains large quantity of coarse aggregate. The void ratio of compacted coarse aggregate ranges between 35% to 50%. In addition, 25% void content has been achieved experimentally by designing gap grading where half of the aggregate ranges between 12-38 mm and the other half ranges between 200-250 mm (ACI 304. R,1997). The high quantity of coarse aggregate in PAC makes the modulus of elasticity higher than that of normal concrete (ACI 304.1R,1997; and Akatsuka and Moriguchi, 1967). Segregation is eliminated because there is no compaction during and after grouting process and due to the homogeneity of the particle distribution (Mehta, 1986; and Neville, 1995).

PAC economy depends on the site conditions and requirement of the work. Experience is necessary in concreting by PAC to get good results where high care has to be taken in the account to prevent grout leakage during grouting and that increases the concrete cost. Moreover forms for PAC are subjected to high pressure during the grout injection; therefore they should be stronger and tighter than normal concrete forms (Troxell et al., 1968; Akatsuka, 1968). On the other hand, concreting by this method needs less cement content compare with conventional one (Abdelgader, 1995; and ACI 304.1R, 1997).

2.2 Historical background

According to Littlejohn (1984), the process of grouted concrete was invented and used on a large scale in 1884 when Kinipple employed the technique at the St. Helier breakwater in Jersey. During 1919-1930 in the USA the method was elaborated by Wertz and later was developed by Davis and others. It is known first by Prepaket method and then by Prepacked concrete and finally Preplaced aggregate concrete (Abdelgader, 1995; and ACI 304.1R, 1997). Colcrete method was developed in the UK (1930-1932), in 1930 the making grout device was constructed and called Colgrout (colloidal grout) and then, Gammon invented the colcrete method in 1932 (Abdelgader, 1995). In Russia, the method was applied in 1926 for facing of the Lenin Wolchowska Dam, it was known as the Lifting Grout Method. In Bratislava (1954-1955), in Czechoslovakia, the method was used under the Activated Grout Method name. Moreover, in Poland the method was developed and has named by Polcrete method at the Technical University of Gdansk by Professor Braun. Polcrete method is similar to Colcrete method in the grout mixing which prepared in a high rotating mixer device called Ultramixer UM (Abdelgader, 1995).

2.3 Applications of preplaced aggregate concrete

In 1938, the preplaced aggregate concrete was used to strengthen the concrete lining of Muir tunnel on the Santa Fe railroad in California, the tunnel length of about 90m. The method was also used to fill the cavity of the Arizona spillway tunnel of Hoover Dam in the USA (Davis et al., 1955). In 1954, Kenamo Penstock tunnel of about 3.3 m diameter and with nearly 780 m static head was backfilled with PAC in British Colombia (Davis et al., 1955).

Barker Dam in the USA was rehabilitated by the method to increase its stability and to eliminate its permeability because of the deteriorated upstream face. Barker dam is 53.34 m high and 213.36 m long, and the grouting processes were continued for 10 days and 16447.37 cubic meter of concrete were achieved (Davis, 1960). Massive amount of concrete of 526315 cubic meters was casted underwater for the piers of Mackinac Bridge in the USA (Davis et al., 1956; and Waddell, 1974).

In the United Kingdom, PAC was used for underpinning at the Barbican. The purpose was to increase the load bearing capacity of 43 story Cromwell and Lauderdale Tower blocks. The concreting operation was lasted one month for each tower block and a total of 2500 cubic meter of preplaced aggregate concrete was casted (Littlejohn, 1984).

In Poland, PAC of about 400 m^3 in the repair of Czchow dam near Cracow and about 350 m^3in the construction of plate foundation of 18-story building in Gdansk were casted (Abdelgader, 1996).

At KoRi nuclear plant, north of Pusan in South Korea, each reactor with its steam generators are located inside a containment vessel. They constructed as a steel cylinder of about 70 m in height and 32 m in diameter with a hemispherical base. Foundation design and construction choice was controlled by the need for intimate contact at the vessel-concrete interface with high strength and absence of thermal cracking. PAC was chosen for the job. An amount of 2000 cubic meter of coarse aggregate was placed together with 270 injection pipes and 235 grout level indicators in 18 days. Therefore, 960 cubic meter of grout was injected within 8 days (Littlejohn and Crawley, 1983).

The method was used also to strengthen and stiffen the Ninian Northern platform in the North Sea. Two corner piles were needed to be filled with high quality concrete. PAC was chosen because the access to each pile interior was limited by a single slot of 1m x 2m cut at sea level and the concrete had to be casted in one continuous process. Two steel perforated pipes of 48mm diameter were placed in each pile. Thereafter, an amount of 217 tonnes of rounded flint aggregate were placed to fill each pile. Finally, Grouting was continued for 15 hours in which 57 cubic meter of grout was injected in each pile (Littlejohn, 1984).

2.4 Preplaced aggregate concrete Grout

2.4.1 Grout constituents

Grout for preplaced aggregate concrete must have enough fluidity to fill the voids of the coarse aggregate skeleton. High Workable grout can be achieved by mixing the ingredients (cement, water and sand) in a high shear mixer such as the Ultramixer or by adding additives and admixtures to the grout ingredients to improve its properties (Neville, 1995; Abdelgader, 1995; Newman and Choo, 2003; ASTM C937, 2003; and ASTM C938, 2003). Grout consistency can be measured as a discharge time of a given quantity of the grout from a special cone called flow cone (ASTM C939, 2003; Domone and Jefferis, 1994). Grout workability can also be measured by the flow-meter test to measure how far a certain quantity of grout can move along horizontal channel after discharged from a special funnel (Domone and Jefferis, 1994, and Littlejohn, 1981). Grout workability will be discussed in more details in section (2.10).

Ordinary Portland cement is widely used for manufacturing of PAC grout; care should be taken in the use of rapid hardening Portland cement because of its increased heat of hydration (Domone and Jefferis, 1994). Non air-entraining cements can be used to make the grout, and that may cause a reduction in the strength when combined with gas–forming fluidifiers, as a result of excessive air quantity in the grout (ACI 304.1R, 1997).

Crushed or natural sands can be used in the manufacture of PAC grout. Sand must be hard, durable and free from impurities. Natural rounded sand is preferred because it needs less water to yield the required grout fluidity (Domone and Jefferis, 1994). Sand shape and gradation are important in use of PAC grout production because of their effect on the fresh grout properties and its ability to pass through the coarse aggregate mass during the grouting. According to ACI 304.1R (1997), using of finer sands in the grout is useful for PAC beams, columns and thin sections at cement-sand (c/s) ratio 1:1 by weight, where the maximum size of coarse aggregate particle is limited by the small dimension of the concrete element. Specifically, it has been stated that the maximum size of coarse aggregate should not exceed the third of the small dimension of the form. It has also been reported that the ratio of minimum particle size of coarse aggregate to the maximum particle size of fine aggregate is 10:1 (Littlejohn, 1984); the former condition takes into account structural considerations where the latter accounts the coarse aggregate mass void ratio to be injected by cement-sand grout. Cement to sand ratio (c/s) ratio can be increased to 1:1.5 in the case of massive concrete works where the minimum size of coarse aggregate is 19 mm. Moreover, the resulted voids from using bigger coarse aggregate are larger in size, hence that will allow thick grouts to penetrate, and then c/s ratio can be increased up to 1:3 if an appropriate grout pumps are used in the injection (ACI 304.1R, 1997).

Normal medium sand grade to BS 882 (1983) is used in the production of grout for PAC (Domone and Jefferis, 1994). According to ACI 304.1R (1997), fine sands with maximum size of about 1.2mm are used to produce grouts to pass through the voids between coarse aggregate as small as 14mm. In addition, grout produced by normal concrete sands, with maximum size of 5 mm can be used in the production of PAC in case of using minimum coarse aggregate size of 40 mm (Dension and Harold, 1991).

Cement replacement additives and chemical admixtures have been used in manufacturing of PAC grout because they improve the properties of the resulting grout and concrete. Additives like fluidifiers and fly ash are usually mixed with cement as a cementatious material by 1:2.5 to 1:3.5, they reduce bleed water and heat of hydration (Neville, 1995; Newman and Choo, 2003; and Dension and Harold, 1991). Admixtures are usually added to the mix in order to improve the grout workability (Witte and Backstrom, 1954). Moreover, super-plasticizers or water reducing admixtures are used to reduce the water content in order to increase concrete compressive strength (Domone and Jefferis, 1994; and ACI 304.1R, 1997). Cohesiveness and fluidity of grout properties can be improved by using the air-entraining admixtures; they are useful to minimize the bleed water in the case of very fine sand not being available (Domone and Jefferis, 1994). There is an advantage of using retarding admixtures in massive concrete to reduce the risk of the cold construction joints and allow more time for casting (Domone and Jefferis, 1994). Aluminum powder is useful when used to produce PAC, since it gives slight expansion before the grout setting takes place (Awal, 1985; Neville, 1995; and Newman and Choo, 2003). The suggested aluminum powder dosage is 1% of the cementitious materials (Awal, 1988 a and b). Polymer modifying admixtures can be used to improve the concrete bond and tensile strength (Domone and Jefferis, 1994). On the other hand, cement- sand grout was used in the production of PAC without using any admixtures and that was in case of large size coarse aggregate, around 100 mm (Littlejohn and Swart, 2003).

2.4.2 Grout workability

A set of lab work was carried out over the period 1993-1995 at the Technical University of Gdansk, Poland by Abdelgader (1995). Materials used in the production of grout and PAC are, Portland cement C35 with fly ash, super-plasticizer of 2% of cement weight, high silica sand with maximum size of 2mm. Three different c/s ratios of 1/0.8, 1/1 and 1/1.5 and four w/c ratios of 1/0.4, 1/0.45, 1/0.50 and 1/0.55 by cement weight were used. Grout was prepared by mixing the constituents in a very high shear mixer (Ultramixer UM6) at rotor speed of 3000 rpm at three different mixing times of 2, 4 and 6 minutes. Grout fluidity was measured by pouring the grout from a 0.25-L volume funnel from 1 cm high on a scaled plate. The fluidity was measured as the diameter of grout propagation. From the regression analysis of the resulted data, the following grout fluidity general equation has been derived (Abdelgader; 1995 and 1999).

$$\text{Fluidity} = \left(b_0 + b_1 * \left(\frac{w}{c}\right)^{b_2}\right) * \left(b_3 + \frac{b_4}{t}\right) * \left(b_5 + b_6 * \left(\frac{c}{s}\right)^{b_7}\right)(m) \tag{2.1}$$

where w/c is the water to cement ratio, c/s is the cement to sand ratio, t is the mixing time of the grout by ultra-mixer machine (min), and $b_0, b_1, \dots \dots \dots .. b_7$ are regression coefficients, as given in Table 2.1. The range of this equation is 70mm ≤ fluidity < 140mm.

Table 2.1 Regression constants to calculate grout fluidity

Regression coefficient	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7
value	2.96	27.82	2.26	2.52	1.13	-3.87	8.03	0.977

From the study of the grout propagation on the target surface, it has been reported that mixing time of 2, 4 and 6 min resulted in variable grout flow. More specific, mixing time longer than 4min resulted in a thick grout where the flow is reduced. For example, grout of w/c ratio of 0.4 and c/s ratio of 1/1.5 does not exhibit enough fluidity, where the grout did not penetrate through the funnel, as a result by injecting this grout into the coarse aggregate mass; the concrete produced is honeycombed (Abdelgader, 1995 and 1999).

2.4.3 Grout compressive strength

From the experimental program described above in section 2.4.2 on grouts, it has been found that compressive strength of the hardened grout prism samples of 40*40*160 mm increases with the duration of mixing at all w/c ratios, because of the increase in the cement specific area due to the high speed of mixing (Abdelgader, 1995 and 1999). Grout strength (f_g) can be calculated by the following formula.

$$f_g = \alpha_0 + \alpha_1 * \left(\frac{w}{c}\right) + \alpha_2 * \left(\frac{c}{s}\right) + \alpha_3 * time \ (MPa) \tag{2.2}$$

where w/c is the water to cement ratio, c/s is the cement to sand ratio, time is the mixing time of the grout by high mixing machine (min), and α_0, α_1 and α_3 are constants obtained from regression analysis as shown in Table 2.2.

Table 2.2 Regression analysis constants of Equation 2.2

Coefficient	α_0	α_1	α_2	α_3
Value	90.88	-117.97	3.56	0.61

Abdelgader, (1995) claimed that the formula derived from the regression analysis on the grout compressive strength can be used as a general equation, where that is not perfectly true because of two reasons; the first, grout compressive strength data are limited in the range of (29.38-51.10) MPa, and the second, because of the term time in the equation is the time required to mix the grout by very high shear mixer. Fairly speaking, the equation can be used to get an approximate compressive strength in the range presented above. Where, the term $(\alpha_3 * time \ )$ can be ignored, because the difference in compressive strength at different mixing times is small for example, between 4min and 6 min the difference in grout strength is 1.22MPa.

2.5 Mechanical Properties of Preplaced Aggregate concrete

2.5.1 Compressive Strength

PAC compressive strength has been investigated for years and compared with that of conventional concrete. It has been reported that its compressive strength is lower than that resulted from normal concrete at early ages, at the same time it is satisfactory from cement content point of view where the cement content is low (Davis et al., 1955; Newman and Choo, 2003; Awal, 1985; and Abdelgader et al., 2004). Although, the authors agree on that the compressive strength of normal concrete is higher than PAC compressive strength at early ages, only Awal (1985 and 1988a) presented an experimental data for comparison to support his claim. He added, the compressive strengths of PAC and normal concrete are nearly the same at age of 90 days of standard curing. Moreover, Awal (1985) also reported that PAC compressive strength at 365 days is higher than that of normal concrete (NC) by using the same w/c ratio without using any admixture in the mix as shown in Figure 2.1.

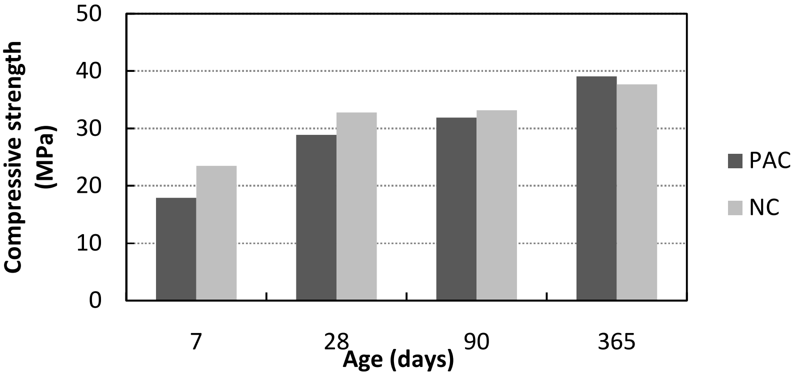


Figure 2.1 Compressive strength vs age for PAC and NC

2.5.1.1 Effect of water content on PAC compressive strength

PAC compressive strength of about 40 MPa has been achieved, where increasing the strength is possible by adding admixtures to the main ingredients of the grout (Neville, 1995; Newman and Choo, 2003; and ACI 304.1R, 1997). PAC compressive strength is directly affected by water-cement ratio as in conventional concrete, as the water-cement ratio increases the compressive strength decreases (Awal, 1985). That is true because, as the high grout workability is essential from the injection process point of view, increasing the w/c ratio to get a required workability will reduce the concrete strength. Then, using of admixtures is necessary to achieve enough grout workability to reduce the w/c ratio in order to improve concrete strength.

2.5.1.2 Effect of additives and admixtures on PAC compressive strength

The strength of PAC is affected also by its grout contents; sand, cement, admixtures and additives similar to conventional concrete. By adding expanding admixtures such as, aluminum powder to the mix, the resulting compressive strength of PAC is higher than that resulted from normal concrete at 7, 28, 90 and 365 days (Awal, 1985). More specific, using a small amount of expanding admixtures increases the strength effectively where it gives the grout some expansion even at early age to increase the bond between the grout and coarse aggregate particles. Using of additives like, fly ash as a cement replacement material can reduce the bleed water because of its high surface area and then enhancing concrete compressive strength.

2.5.1.3 Effect of curing condition on PAC compressive strength

Ganaw (2002) and Abdelgader et al. (2004) reported that, there is high difference in the compressive strength ratio between water and air cured PAC cubes at 28 days compared with normal concrete as shown in Figure 2.2. The high amount of coarse aggregate in PAC means higher bond transition zone area between grout and aggregate. And that makes PAC more sensitive to the curing condition. Then good curing condition should be taken into account when PAC produced.

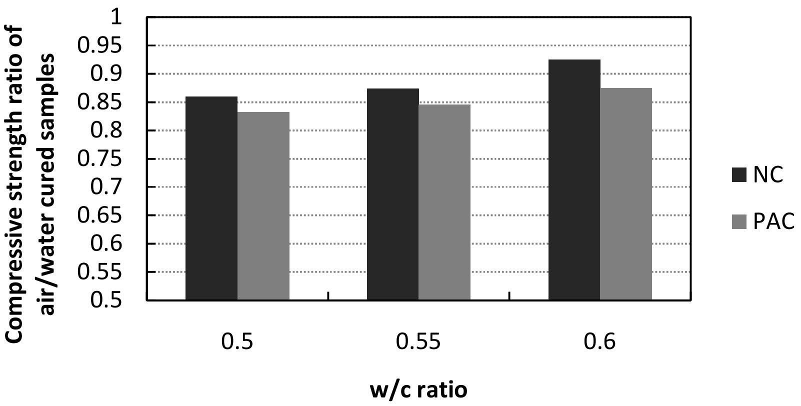


Figure 2.2 Compressive strength ratio of water / air cured concrete vs w/c ratio for NC and PAC

2.5.1.4 Effect of coarse aggregate on PAC compressive strength

The coarse aggregate used in the production of PAC has a major effect on the resulting PAC properties because of its high quantity and the contact between its particles. It is stated that the volume of coarse aggregate in PAC is about 65-70% (Neville, 1995; and Newman and Choo, 2003).

Abdelgader (1995) investigated the effect of different types of coarse aggregates on the production of PAC. The coarse aggregates used in the study were rounded, crushed and mixed. The rounded aggregate was 100 mm maximum aggregate size in which the quantity of particles greater than 80 mm was less than 8%. The crushed aggregate was 63 mm maximum size. Finally, the rounded aggregate was mixed with the crushed aggregate by volume at 1/1. He reported that there is a difference in PAC compressive strength by using different types of coarse aggregates at the same grout strength. More specific, using crushed coarse aggregate gives higher PAC compressive strength than does rounded coarse aggregate, due to the rough surface of crushed aggregate which increases the bond between coarse aggregate and mortar. He added, by mixing crushed and rounded aggregates, the resulted PAC compressive strength is higher than that using them separately at the same grout strength. Data presented in the investigation supports what Abdelgader (1995) has reported and hence, forwards this discussion; the smooth surface of rounded aggregate reduces the bond with the grout, and that caused the reduction in strength compared with crushed aggregate which contains rough surface. Mixing of both types of coarse aggregate yields higher strength than does separately because of the less void ratio of the mixed than that of crushed coarse aggregate. In other words more interlocking between the grout and the coarse aggregates resulted from mixing.

In conclusion, comparison between PAC and conventional concrete is complicated and comparison on the basis of w/c , compressive strength is not fair due to the high amount of coarse aggregate in PAC, the contact and interlocking between coarse aggregate particles, grout quantity and injection process affect on the properties of resulted concrete.

2.5.1.5 PAC mix design

An algorithm for the design of PAC has been reported by Abdelgader (1995 and 1999) as shown in Equation 2.3. In the investigation, the mix proportions of the grout were calculated according to the absolute volume equation as following:

$$w + C/\rho_c + S/\rho_s = e * 1000 \tag{2.3}$$

where w is the water weight in kg, e is the void ratio of compacted coarse aggregate, C is the cement weight (kg/m^3), S is the sand weight (kg/m^3) and $\rho_c\ and\ \rho_s$ are specific gravity of cement and sand respectively.

From the experimental data, the general PAC compressive strength equation has derived by Abdelgader (1995, 1999) and shown as follows

$$f_c' = \gamma_0 + \gamma_1 * \left(\frac{w}{c}\right) + \gamma_2 * \left(\frac{c}{s}\right) + \gamma_3 * time \tag{2.4}$$

where f_c' is the compressive strength of PAC (MPa), w/c is the water-cement ratio, c/s is the cement-sand ratio, $time$ is the mixing time and $\gamma_{0,} \gamma_{1,}\ \gamma_2$ and γ_0 are regression constants, as shown in Table 2.3

Table 2.3 Regression analysis constants for Equation 2.4

coarse aggregate	**Void ratio (%)**	γ_0	γ_1	γ_2	γ_3
Rounded	39	63.43	-75.25	-0.06	0.21
Crushed	47	61.24	-71.00	0.52	0.21
Mixed	43	64.26	-75.33	0.26	0.13

Abdelgader claimed that this formula derived from the regression analysis on PAC compressive strength can be used as a general equation for the design of PAC. As a comment, this is not perfectly true as presented in the effect of different factors on grout strength in section 2.4.3, because PAC compressive strength range has not presented and the time required to mix the grout is measured by very high shear mixer. Consequently, the equation can be used to predict compressive strength of PAC in the range tested for each type of coarse aggregate in his investigation. The term $(\gamma_3 * time)$ can be ignored because of the small effect of mixing time change on compressive strength for example, between 4 min and 6 min the difference in grout strength is less than 1 MPa for all cases as a result from the equation.

2.5.1.6 Effect of grout compressive strength on PAC compressive strength

Abdelgader (1995 and 1999) reported that the dependency of PAC compressive strength on its grout strength according to an experimental work can be obtained from this relation:

$$f_c' = \beta_0 + \beta_1 * f_g^{-\beta_2} \tag{2.5}$$

Where f_c', f_g are PAC and grout compressive strengths respectively (MPa) and $\beta_0, \beta_1, \beta_2$ are regression analysis constants, as shown in Table 2.4.

The validity of equation 2.5 depends on grout compressive strength of 29.38 - 52.10 MPa (Abdelgader 1995 and 1999).

Table 2.4 Empirical constants for Equation 2.5

Kind of aggregate	β_0	β_1	β_2
Rounded	9.56	0.14	1.32
Crushed	6.70	0.42	1.07
Mixed	7.37	0.32	1.14

Abdelgader (1999) reported that an increase by 80% in grout compressive strength causes 60 - 65% increase in PAC compressive strength, and that may be related to the contact points of coarse aggregate particles and the bond between the coarse aggregate and hardened grout. Looking at equation 2.5 shows that Abdelgader`s claim is correct because the first term (β_0) is not affected by grout compressive strength. Hence, this supports the claim where there are other factors affecting the PAC compressive strength in the range tested.

2.5.2 Tensile Strength

Tensile strength of PAC is affected mainly by the water-cement ratio of the grout, where the cement-sand ratio has some effect. PAC tensile strength is increased with an increase in its compressive strength (Awal, 1985; Abdelgader and Ben-Zeitun; 2004, 2005).

Awal (1985) reported that PAC shows higher tensile strength than does conventional concrete. He related that to the high quantity of coarse aggregate and the high mechanical interlocking between particles. Awal got this conclusion from the data presented in his investigation, in which PAC tensile strength is higher than that of conventional concrete for all grout mixes. From the regression analysis of the splitting tensile strength, Awal (1985) suggested the following formula for the relationship between tensile and compressive strengths of PAC.

$$f_{tp} = 0.677\ (f_c')^{0.434} \qquad (2.6)$$

where f_{tp} is the tensile strength and f_c' is the compressive strength of PAC .

Abdelgader and Ben-Zeitun (2004) used the splitting tensile strength test to measure the tensile strength of PAC, they presented the following formula;

$$f_{tp} = 0.768 * (f_c')^{0.441} \qquad (2.7)$$

where f_{tp} is the split tensile strength of PAC at 28 days (MPa), f_c' is the compressive strength of PAC.

From the investigations presented above, there is a good agreement in the splitting tensile strength equations (2.6) and (2.7) for both investigations. Then, it can be summarized that, the tensile strength formula resulted from the splitting tensile test is appropriate to define the relation between tensile and compressive strengths of PAC.

2.5.3 Shrinkage and creep

It is reported that the shrinkage and creep of PAC are much less than these of normal concrete (Davis, 1960; Awal, 1985). The big difference in drying shrinkage and creep is due to the huge amount of coarse aggregate used and because of the contact points between coarse aggregate particles. It has also been reported by Awal (1985) that additives and admixtures have a significant effect on the shrinkage of PAC. He reported that, PAC contains expanding admixture show higher shrinkage than does the non-added material PAC. On the other hand, the lowest shrinkage presented by PAC contains super-plasticizers. Awal showed some relationships between concrete age and drying shrinkage for different concrete mixes. The use of super-plasticizers which reduces the w/c ratio may be helped in lowering the drying shrinkage comparing with other PAC samples.

It has been reported by Awal (1985), that PAC with super-plasticizers has presented relatively low creep than do other samples. It is difficult to do a comparison between data presented by Awal in his study because of the difference in w/c ratio used by using different admixtures. At the same time, it is not fair to compare PAC with normal concrete because of the difference between them in the amount of coarse aggregate, the contact of coarse aggregate particles and the amount of cement paste.

It is reported by Davis et al. (1956) that creep of PAC decreases between 7 and 28 days and then increases at 90 days. On the other hand, Awal (1992) presented a relation between creep and age for normal concrete and PAC, showing that creep increases with an increase of time for both types of concrete. In addition, conventional concrete shows higher creep than PAC at the same age. The lower creep value of PAC is attributed to the contact points between coarse aggregate particles.

2.5.4 Stress strain relationship and modulus of elasticity

PAC stress-strain relationship increases linearly until nearly the peak then, it concaves at the peak and falls down, the relation occurs even for early ages PAC (two weeks) (Davis et al., 1955; Akatsuka and Moriguchi, 1967; and Awal, 1988b). On the other hand stress-strain diagrams of normal concrete are concave at early ages at low strength. The effect of point to point contact between coarse aggregate particles of PAC has an elastic behavior even at early ages (Davis et al., 1955).

Akatsuka and Moriguchi (1967) reported that stress-strain relationship of PAC shows similar behavior comparing with normal concrete. They added, no essential difference has found on the elastic and plastic deformation between the two concretes, irrespective of the fact, the modulus of elasticity of PAC is larger than that of normal concrete.

Modulus of elasticity of concrete in general increases with an increase in compressive strength; there is no exact form of the relation as reported by Neville (1995). He added, the modulus of elasticity of concrete is affected by the modulus of the aggregate and by its volume content. It has been reported that, modulus of elasticity of PAC is higher than that of conventional concrete (Davis et al., 1955; Akatsuka and Moriguchi, 1967; and ACI 304.1R, 1997). Similarly, Awal (1985, and 1988b) stated that the modulus of elasticity of PAC is higher than that of normal concrete (NC) at all ages of curing using different additives and admixtures. Although, the same piece of information has presented in many investigations, only Awal (1985, 1988b) has presented experimental data as an evidence for his claim, as shown in Figure 2.3. The high modulus of elasticity of PAC is related to the high amount of coarse aggregate and, to the contact between its particles.

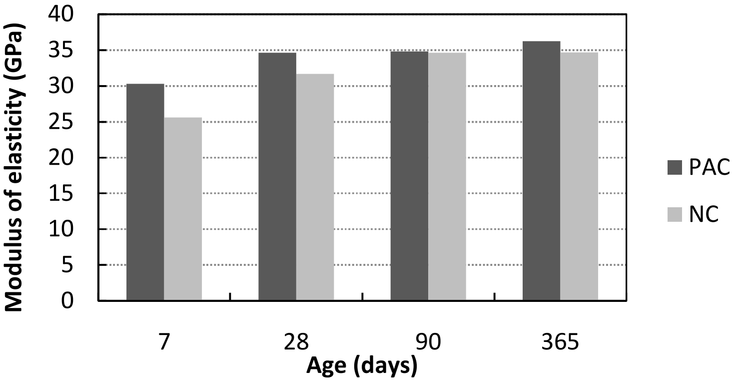


Figure 2.3 Modulus of elasticity vs age for non admixture PAC and NC

In the underground construction of Penstock tunnel which was backfilled with PAC (Davis et al., 1955) a number of 250*500 mm PAC cylinders were tested. Materials used are, cement and sand at ratio of 1/1, fly ash called Alfesil at 43% of the cement weight as a cement replacement material and an intrusion aid at 1% of cementatious materials weight. It was found that the compressive strength increased from nearly 13.8 MPa at two weeks to nearly 24 MPa at three months and the secant modulus of elasticity increased from nearly 20 GPa at two weeks to nearly 24 GPa at three months. The presented values show that the compressive strength of PAC increases with time more rapidly than does the modulus of elasticity (Davis et al., 1955). That is the same for normal concrete where, the increase in modulus of elasticity of normal concrete is lower than the increase in compressive strength (Neville, 1995). However, there is no available data in the literature for detailed comparison.

A series of laboratory tests were performed on 196mm x 392mm cylindrical PAC samples by Abdelgader and Gorski (2001, 2002). Twenty seven cylindrical PAC were prepared, three samples of each grout mixes with 3 w/c and 3 c/s ratios. Obtained stress-strain curves were linear up to 30% of the compressive strength. Modulus of elasticity value was taken as a tangent of the stress-strain curve at 30% of the cylindrical strength samples. The relation between modulus of elasticity and compressive strength of PAC was calculated by using the least square method and presented as follows

$$E = 21.55 + 0.03 f_c' \tag{2.8}$$

where E is the modulus of elasticity (GPa) and f_c' is the compressive strength of PAC (MPa). The validity of the formula is in this range; $21.5 \leq E \leq 24.5$ (GPa).

2.6 Failure mechanism of PAC

It has reported by Abdelgader (1995) and Awal (1985, and 1988a) that the crack failure of PAC occurs through the coarse aggregate particles as well as the hardened grout. And that failure has occurred in the coarse aggregate particles where the concrete compressive strength was around 40MPa. This forwards this possibility, the high stress concentration resulted at the contact points of coarse aggregate particles is the responsible behind the aggregate failure at relatively low compressive strength.

Abdelgader (1995) claimed that the failure of PAC occurs through the coarse aggregate particles first then, to the hardened grout. Moreover, micro-cracks in the grout start to appear at load range of 70-80% of the ultimate load. Because of no evidence supporting this claim makes the possibility of coarse aggregate failure first inaccurate. Awal (1985, 1988a) has reported that the failure of PAC in compression is not sudden and explosive like normal concrete. It was extensively expanded laterally in the form of bulging before failure occurred. That could be normal because the compressive strength resulted from his work on PAC was not high enough to give sudden or explosive failure.

The contact between stone particles in all directions makes the stresses in the aggregate particles and in the grout cannot be equal. The stress distribution produces shear stress and stress concentration at the contacted points of the coarse aggregate particles, these stresses cause fracture of the stones (Abdelgader and Gorski; 2001 and 2002). In other words, the mechanism of PAC coarse aggregate failure can be explained by the stress concentration at the contacted points. Consequently, the increase in shear stresses effectively affected the failure process.

2.7 Analysis of PAC data presented by Abdelgader (1995)

Abdelgader (1995) presented a high quantity of experimental results on grouts and PAC at different w/c, c/s, grout mixing time and coarse aggregate types. Relations between fresh grout fluidity and concrete compressive strengths of PAC will be represented. Since, without enough fluidity, the injected grout will not penetrate the compacted coarse aggregate mass. On the other hand, the high increase in grout fluidity resulting from the high water content will adversely affect the compressive strength of PAC. The lack of such information on the relation between grout fluidity and PAC leads to represent the data of the investigation mentioned above; some important points are summarized below.

2.7.1 Effect of fluidity on the compressive strength of the grout and PAC.

Figures 2.4, 2.5 and 2.6 show that the compressive strength for both hardened grout and PAC is a function of both grout fluidity for c/s ratios of 1/0.8, 1/1 and 1/1.5 by weight respectively (Abdelgader, 1995). Grout fluidity was measured as the diameter of grout released from cylinder of 0.25 liter volume from 1 cm height on a scaled plate. As the fluidity increases the compressive strength decreases for both grout and concrete. It is apparent that grout compressive strength is higher than concrete compressive strength for all c/s ratios. The low compressive strength in PAC is attributed to the weak bond between grout and coarse aggregate or to the failure in coarse aggregate particles due to the high stress concentrations at the contact points.

It is clear that concrete compressive strength was affected by the degree of grout workability. More specific, at low grout fluidity values, concrete compressive strength increases with an increase in grout workability until reaching its peak as shown in Figure 2.6. After the peak, concrete compressive strength decreases with an increase in grout fluidity as shown in Figures 2.4, 2.5 and 2.6. In the first part of the relation, as the grout fluidity increases more coarse aggregate voids filled with grout which results in more compressive strength of concrete. Full grout injection through the coarse aggregate gives maximum concrete compressive strength at the peak. Further grout workability results in full penetration through the coarse aggregate but because of this excess in fluidity comes from the high water content the concrete compressive strength decreases.

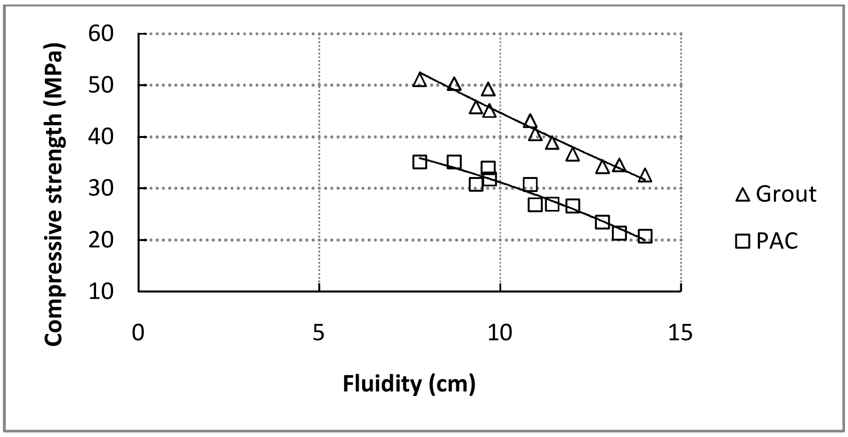


Figure 2.4 Fluidity versus compressive strength of grout and PAC at c/s ratio of 1/0.8

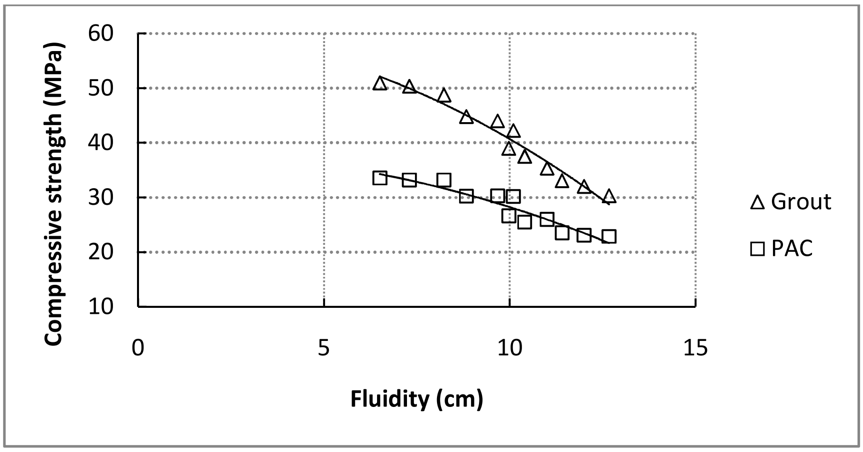


Figure 2.5 Fluidity versus compressive strength of grout and PAC at c/s ratio of 1/1

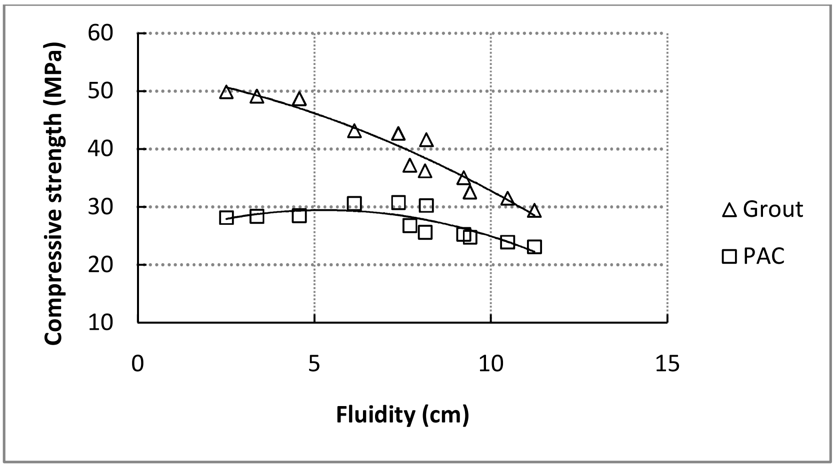


Figure 2.6 Fluidity versus compressive strength of grout and PAC at c/s ratio of 1/1.5

2.7.2 Relationship between concrete-grout compressive strength ratio and grout fluidity

Figure 2.7 shows the effect of grout fluidity on concrete-grout strength ratio at c/s of 1/0.8 by weight, as the grout fluidity increases the strength ratio slightly increases until a certain values at which the strength ratio decreases with an increase in grout fluidity. This is attributed to the improvement in grout injection through the coarse aggregate as its fluidity increases until the full injection occurs, after which any further fluidity affects adversely on the compressive strength due to the increase in water content. Figures 2.8 and 2.9 show that the PAC/grout strength ratio is a function of grout fluidity at c/s ratios of 1/1 and 1/1.5. Strength ratio increases significantly with an increase of grout fluidity for c/s ratios of 1/1 and 1/1.5. Moreover, at c/s ratio of 1/1.5 the relation is too inclined than that of c/s ratio of 1/1, this increase could be attributed to the effect of better bond between hardened grout and aggregate because of the increase in high sand amount which reduces the bleed water.

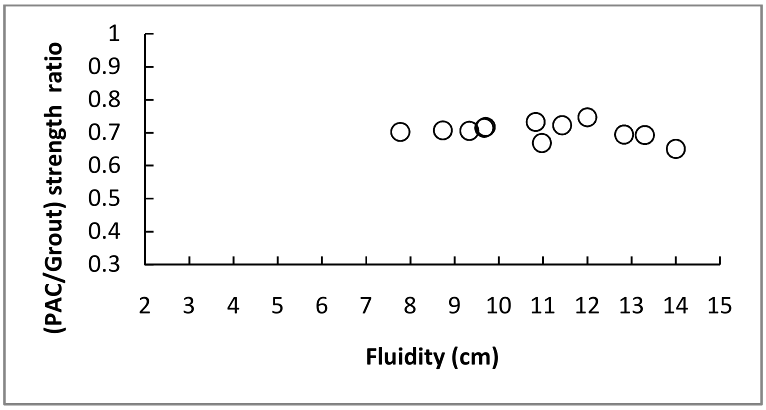


Figure 2.7 Fluidity versus PAC/grout strength ratio at c/s ratio of 1/0.8

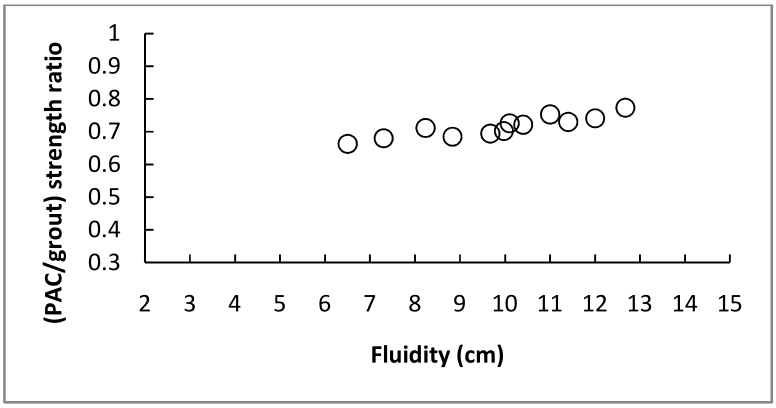


Figure 2.8 Fluidity versus PAC/grout strength ratio at c/s ratio of 1/1

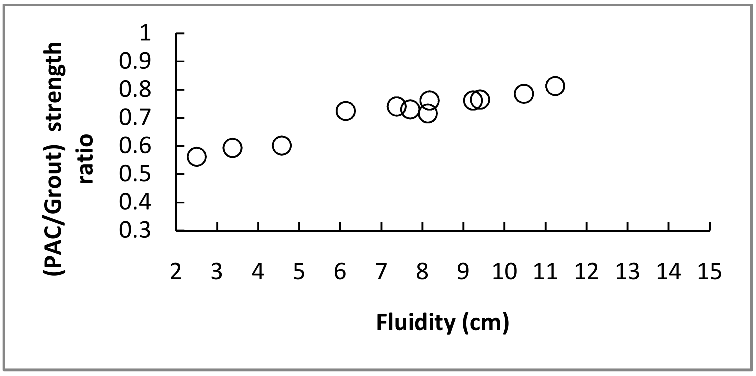


Figure 2.9 Fluidity versus PAC/grout strength ratio at c/s ratio of 1/1.5

Finally, from the relations presented above, it can be concluded that grout fluidity affects directly on the compressive strength of resulted concrete depending on the ability of grout to penetrate through the coarse aggregate in the second stage of PAC production. Furthermore, as the full grout injection through the coarse aggregate occurs, any further fluidity of the grout will affect adversely on the compressive strength of the resulted concrete. And that is because the excess in fluidity resulted from the increase in water content in the grout.

From the presented analysis of the effect of grout fluidity on the resulted PAC, it can be concluded that grout flow ability is of great importance in the production of PAC. The grout has to be fluid enough to fill up the voids among coarse aggregate mass.

Tattersal (1991) reported that for full understanding of the material behavior like fresh grout and concrete, yield stress and plastic viscosity parameters are important, because some materials have the same yield stress but different viscosity or the opposite. Consequently, there is a need to study the science of rheology which is presented below.

2.8 Definition of Rheology

Rheology is the science of the deformation and matter flow; it is concerned with the relations between stress, strain and time. Because of the importance of flow and movement of cement based materials, it is worth studying the relationships between shear stress and rate of strain (Powers, 1968; and Tattersal and Banfill, 1983).

Cement based materials in their fresh state behave as non Newtonian fluids according to Bingham model as shown in Table 2.5, and that means two constants, yield stress and plastic viscosity are necessary to define the material behavior (Newman and Choo, 2003). The flow curves of a fluid can be plotted from the relation between its shear rate and shear stress as shown in Figure (2.10a), the rheological properties can be calculated from the down curves of shear rate–shear stress relationships as shown in Figure (2.10b).

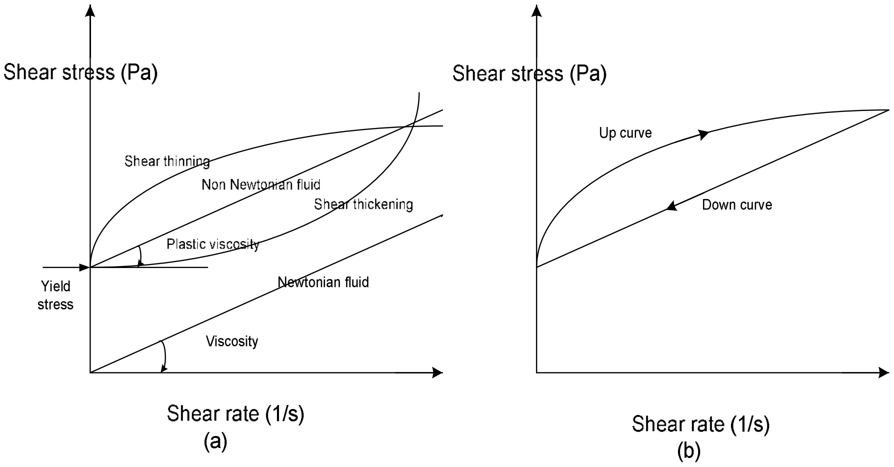


Figure 2.10 Flow curves

Thixotropy is one of the important parameters of rheology, where the viscosity of the material decreases with time under a constant shear. The shear rate is first increased to a certain point to give the up curve as shown in Figure (2.10 b) then, decreased the shear rate to the starting point to give the down curve, this is called Hysteresis loop. In this loop, the difference between up and down curves has caused by the material structural breakdown. Structural breakdown changes the material viscosity as shown in the up curve, and then, at a certain point the material viscosity becomes constant at the end of up curve. That means there is no more structural breakdown as shown in the down curve where the slop constant. The smaller difference in the hysteresis loop between curves (smaller area) means that the material has less structural breakdown by the viscometer, in other words the material was broken down in the grout mixer not in the viscometer during the test (Banfill, 2003). Most of the common flow curves of flow materials are shown in Figure (2.10a). The simplest fluid is that behaving as a Newtonian without the yield stress term. On the other hand, Bingham fluid needs some stress to start flow, and both fluids have a constant viscosity. The viscosity of materials with shear thinning behavior decreases as the shear rate increases, whereas shear thickening material viscosity increases with an increase in shear rate (Newman and Choo, 2003). The most common flow curves relationships between shear rate and shear stress are shown in Table 2.5.

Table 2.5 Common flow curves relationships between shear rate and shear stress

Model	**Equation**	**Author and date**
Newtonian	$\tau = \eta \nu^{\cdot}$	Bager et al 2001
Bingham	$\tau = \tau_0 + \eta \nu^{\cdot}$	Bager et al. 2001 ; Yahia and Khayat,2001and Banfill, 2003
Modified Bingham	$\tau = \tau_0 + \eta \nu + \mathrm{B}\, \nu^2$	Yahia and Khayat,2001and Banfill, 2003
Herschel-Bulkley	$\tau = \tau_0 + \mathrm{A} \nu^B$	Yahia and Khayat,2001, Banfill, 2003 and Banfill and Frias 2006
Casson	$\tau = \tau_0 + \eta \nu^{\cdot} + 2(\sqrt{\tau_0 \eta})\sqrt{\nu^{\cdot}}$	Yahia and Khayat,2001
De Kee	$\tau = \tau_0 + \eta \nu^{\cdot} e^{-A\nu^{\cdot}}$	Yahia and Khayat,2001
Yahia and Khayat	$\tau = \tau_0 + 2(\sqrt{\tau_0 \eta_\infty})\sqrt{\nu^{\cdot}} e^{-A\nu^{\cdot}}$	Yahia and Khayat, 2001 and Banfill, 2003
Robertson-Stiff	$\tau = A(\nu^{\cdot} + B)^C$	Banfill, 2003

where τ is the shear stress (Pa), η is the plastic viscosity (Pa.s), $\nu^{\cdot}$ is the shear rate (s^{-1}), τ_0 is the yield stress (Pa), $\eta_\infty$is the viscosity at very high shear rate (Pa.s) and A,B,C are constants.

Yahia and Khayat (2001) compared some of the equations mentioned for describing the yield stress for cement based grouts by using additives and admixtures in the mixes. They reported that there is a difference in the yield stress value from Bingham, Casson, Herschel-Bulkley, Yahia and Khayat and De Kee rheological models presented in Table 2.5, the difference is greater for pseudo-plastic grouts.

Banfill (2003) reported that the available values for cement paste and grout in rheological parameters over a wide range cannot be explained by the materials variations but by the differences in experimental technique and apparatus used. He added, the differences are the shear history of the sample at the test time, undetected plug flow and slippage resulted from the smooth surface of the viscometer. These factors can be combined to give a large experimental differences as those reported in the previous equations.

Banfill and Frias (2007) investigated the rheology of cement paste with and without super-plasticizers. However they reported that flow curves could be analyzed by the Herschel-Bulkley equation, they preferred to use Bingham model in their investigation because it is more reliable. Similarly, several researchers stated that fresh mortar flow curves conform to the Bingham model and it is necessary to measure two factors, yield stress and plastic viscosity to understand the flow behavior (Banfill, 1991; Banfill et.al 2006, Banfill, 2003, Seabra et. al 2007; Golaszewski and Szwabowski, 2003 and Erdogan et al 2008).

2.9 Rheology comparison between cement paste, grout, mortar and concrete

A wide range in rheological parameters of cement based materials based on Bingham model is shown in Table 2.6 (Banfill, 2003).

Table 2.6 Cement based materials rheological parameters

Material	**Cement paste and grout**	**Mortar**	**Flowing concrete**	**Self compact-ting concrete**
Yield stress (Pa)	10-100	80-400	400	50-200
Plastic viscosity (Pa. s)	0.01-1	1-3	20	20-100

It is clear that yield stress and viscosity values are in this sequence; cement paste, grout, mortar and concrete. These high values of rheology in mortar and concrete have come from the increase in maximum particle size which is able to resist the applied stresses without deformation; this also can be happened by increasing the aggregate content in mortar and concrete. In contrast, mortars with more fines have resulted in higher shear stress and plastic viscosity (Banfill, 1993), and that is attributed to the effect of cement paste-aggregate interface in the system. In other words, as the fines increase the surface area increases which needs more cement paste to cover the sand surface and to give a certain rheological values to the mortar. Consequently, for constant cement paste volume, the higher sand surface area results in higher yield stress and plastic viscosity of mortar. It is clear that the effect of particle size is the surface area in fine grained cement based materials rheology and a simple volume effect in coarser grained materials like concrete.

However, the presented values of yield stress and plastic viscosity are in their absolute units of Pa and Pa.s respectively, the Viskomate NT rheometer presented later in section 2.10.2 gives yield stress parameter in Nmm and plastic viscosity parameter in Nmms. Typical values of g and h for mortar reported by Banfill (1995) are in the range 5 – 50 Nmm and 1- 6 Nmms.

2.10 Workability test methods

It is very important to know the flow properties of fresh mortar relating to its products. In addition, if the effect of mortar constituents on its workability is known then, the quality of the production at a certain time can be controlled rather than waiting for the hardened material to be tested. Correct definition of workability may provide information which used for formulation and relevance of hardened material and in choosing of ingredients (Banfill, 1993). Flow properties of cement based materials are fairly measured by two point tests which is the rheology rather than a single test (Tattersal, 1991). In the two point test there is a need to measure the yield stress and plastic viscosity of the fresh material (Tattersal, 1991; and Banfill and Tattersal, 1983). Tattersal (1991) classified the workability test methods to three categories due to the large number of workability test methods as given in Table 2.7. Although the flow properties of fresh mortar considered as model concrete and give useful information to the workability of concrete (Banfill, 1993), most of the categories in the table are not suitable for mortar. Moreover, since this research mainly concerned with the flow of mortar or grout and its effect on the production of PAC then, concrete workability is not covered in this literature review.

Table 2.7 Cement based materials workability classification

Class 1 Qualitative: Workability, Flowability, Compactability, Stability, Finishability and Pumbability, etc	This is only used in a general descriptive way without any attempt to quantify.
Class 2 Quantitative empirical: Slump, Compacting factor, Vebe time and Flow table spread, etc	This is used as a simple quantitative statement of behavior in a particular set of circumstances.
Class 3 Quantitative fundamental: Viscosity, Mobility, Fluidity and yield value	This is used strictly in conformity with standard definitions

Single point test of workability can only measure one factor of rheological parameters which lead to incomplete workability description. For instance, slump test can only measure the yield stress. Rheology can measure two points on the flow curve which give complete description on material flow. Fairly speaking, although single point tests can not show the whole rheology behaviour, they are simple and rapid which make them sometimes appropriate for some situations (Hu, 2005).

2.10.1 One point tests

2.10.1.1 Flow table test

In this test, a certain amount of mortar spread is measured after it is dropped a number of 15 times in 15 seconds on a metal sheet (BS EN 1015-3, 1999). More workable mortar results in higher spread diameter. As the mortar dropped it is subjected to stress higher than the yield stress then, the result may considered to be related to the viscosity (Tattersal, 1991). Because the metal sheet diameter is limited, this test can measure only low and medium workability mortars.

2.10.1.2 Mini slump test

It is a kind of free flow test methods in which a certain amount of mortar or grout is released from a small funnel and left to flow under its own weight. The final diameter gives an indication on the material flow (Abdelgader, 1995), more fluidity gives higher diameter. The test is simple and can be repeated, it is practical in the lab and the field. The result of the test is related directly to the yield stress because the spread is decided by the stress resulted from the gravity of material (Murata and Kikukawa, 1992).

2.10.1.3 Colcrete flow meter

Flow of a known volume of grout through a horizontal channel is one of the methods by which grout fluidity can be defined. In the flow meter test a quantity of 1.13 liters of grout is released to flow through an open scaled channel, the flow is defined by distance of the grout transmission in (cm), (ACI 304.1R, 1969).

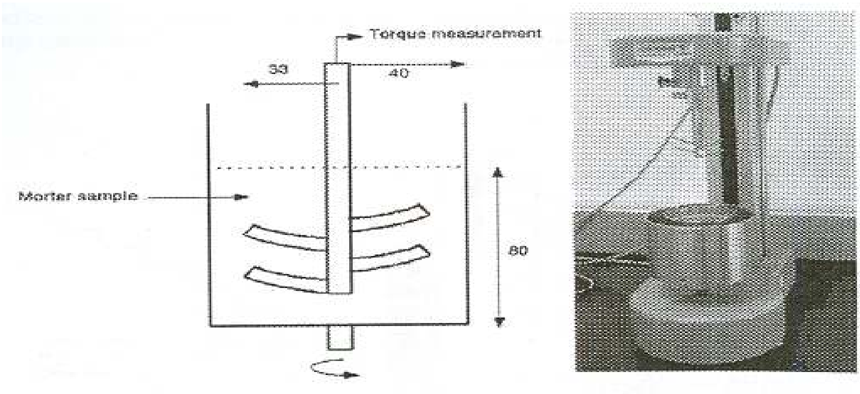
2.10.1.4 Flow cone test

Grout fluidity can be defined by the required time in seconds to discharge 1725ml of grout from a standard funnel (ASTM - C 939, 2002).

2.10.2 Two point test

Rotational rheometers or viscometers like Viskomat NT are devices which measure the shear stress under applying different shear rates in order to get the flow curves of mortar.

From the flow curves rheological parameters can be calculated. Viscomat NT as shown in Figure (2.11), consists of a cylindrical container which carries about 1 kg of mortar, this cylinder is fixed on a variable speed rotating turn table. During the cup rotation, a concentric paddle is inserted into the mortar and mounted on a torque measuring head. As mortar flows through the blades of the paddle, generates a torque continuously due to blades resistance. This torque is registered electronically at a predetermined speed program over a period of time, all of this operation is controlled by a software in a personal computer. When the test completed, all readings of speed, torque, temperature and time are filed by the computer and then, can be displayed or printed graphically (Banfill, 1995; Banfill et al, 2006). The sample temperature can be controlled or kept constant by circulating water in the gap between the outer and inner cylinders. Mortar with maximum particle size of 2mm can be measured because it can flow in the gap between the blades and the inner surface of the cylinder.



All dimensions are in mm

Figure 2.11 Viskomat NT rheometer

Mortar flow curves can be plotted from readings in the form of speed, N against torque, T and it is confirmed that mortar flow obeys Bingham model as follow

$$T=g + h\,N \tag{2.9}$$

Where, g and h are constants which proportional to yield stress and plastic viscosity respectively, (Banfill, 1991; Paiva et al 2006; and Seabra et al, 2007). The viskomat is able to give information on the rheology of mortar and related products with high degree of sensitivity and discrimination (Banfill, 1994).

2.11 Factors affecting on rheology

Rheology of cement based materials is affected by the material constituents and every condition of manufacturing. Moreover, factors influencing cement based materials rheology are the water content, cement properties and quality, properties and quantity of sand used, type and percentage of additives and admixtures, mixing time and method , temperature and age of the fresh material.

2.11.1 Water content

As in mortar or cement paste workability, water is the most important factor controlling mortar rheology. Yield stress and plastic viscosity decrease with an increase in water content for both mortar and cement paste (Tattersal and Banfill, 1983; Newman and Choo, 2003; and Hu, 2005) and that attributes to the liberation of the solid particles in the mix with an increase in water content.

2.11.2 Cement

Nunes et al., (2010) reported that chemical and physical properties of cement are correlated to the rheology of paste, according to their investigation on four different cements. In addition, they reported also that chemical composition of cement is significantly correlated to T funnel test. Moreover, cement surface area is significantly affected the flow diameter of paste measured by the mini slump test.

Golaszewski and Szwabowski (2004) studied the effect of two super-plasticizers on the rheology of mortars by using three commercial cements. They found that chemical and phase composition of the cement are important factors for the performance of super-plasticizers. Moreover, grout of a certain super-plasticizer and dosage results in clear difference in the rheological properties by using different cements.

Vikan, et al (2007) found that the flow resistant of cement paste well correlated with the cement properties ($\text{Blaine}.\{d.C_3A + [1-d].C_3S\}$), where d is the relative reactivity of cubic C_3A and C_3S where C_3A and C_3S represent the content of these minerals. They found that either a linear or exponential function of the combined cement properties depending on plasticizer type and dosage.

It is clear that cement properties affect paste and mortar rheology. For instance, increase of cement fineness needs more water because of the increase of surface area. And if the water kept constant the resulting paste or grout will show lower workability, in other words higher flow resistance will occurs. Chemical composition of different cements has an effect on paste and grout rheology because of the change in hydration speed at the same water content because of the difference in reactivity.

2.11.3 Sand

Effect of sand on mortar workability is important because the sand particle size influences the amount of water requirement, consquently, the finer sands need more water content to attain certain workability. Sand gradation, shape and texture also affect mortar workability or rheology for instant, the more spherical the particles the higher flow the mortar will be, effect of different sand properties on mortar rheology are shown as follows:

2.11.3.1 Effect of particle size

Banfill (1995) measured the rheology of mortars of three different grading sands. He found that the yield stress increases with an increase in sand fineness, and he related that to the attraction forces between the particles. He added, the finer particles have greater surface area which results in more contact between sand particles and results in higher attraction points. He reported that the plastic viscosity resulted from the medium fineness sand was the highest where other sand mortars show the same. In other investigation, Banfill (1999) reported that the increase of sand percentage passing 300μm progressively increases the yield stress and decreases the plastic viscosity in mortar. In both investigations, the increase in sand fineness and surface area at same paste content show an increase in mortar yield stress because of the increases in sand contact points which increase the friction among mortar ingredients. The plastic viscosity trend in the second investigation was clear because the sand surface area was presented by the quantity passed 300μm. Moreover, as the sand surface area increases more cement paste needed to cover its surfaces, and because the paste kept constant in mortar less plastic viscosity was resulted.

Westerholm et al. (2007) reported that, using crushed fine aggregate in mortar results in higher values of yield stress and higher plastic viscosity; they attributed that to the high amount of fineness available in crushed sand which increases the inter-particle friction during the test. Similarly, Hu and Wang (2007) reported that, for a given mix proportion, the larger particles in the mortar usually has higher flow ability due to the lower un-compacted voids in sand which consumes less cement paste where the other paste gives the mortar higher flow. That means, one part of the cement paste fills the un-compacted sand voids and the other part covers the sand particles and separate the particles from contacting each other, more paste gives more separation by thicker paste layer which gives more flow to the mortar.

2.11.3.2 Aggregate gradation

Graded aggregate gives the mortar higher flow ability than single size aggregate because it contain different sizes which means, the smaller aggregate can fill the voids among the bigger particles, and that leads to low void content within the aggregate and resulting in more paste remain after filling the voids. This excess paste will enhance the flow ability; it separates the aggregate by a layer of paste, the thicker the layer results in higher flow to the mortar (Hu and Wang, 2007).

2.11.3.3 Effect of aggregate shape and texture

Particle shape of sand affects mortar workability because of its effect on the un-compacted volume of voids, and that affects directly on the cement paste volume required for mortar wokability. Therefore, a larger quantity of cement paste is required to attain enough workability in case of using angular crushed fine aggregate, instead of natural rounded aggregate with the same grain size distribution (Cortes et al., 2008).

Similarly, Hu and Wang (2007) confirmed that aggregate type significantly influences mortar flow. Moreover, for a certain mix proportion, mortar made with river sand has a higher flow than that made with limestone aggregates. They attributed that to the higher angularity of limestone which contains higher un-compacted void content than river sand which need more paste to fill them. The irregular shape and rough surface texture results in higher interlocking in mortar and more friction between aggregate particles which require more energy for starting and processing the flow. Westerholm et al (2007) related the high plastic viscosity in mortar to the particle shape effect.

2.11.3.4 Effect of aggregate content

Flow ability of mortar significantly decreases as the sand content increases due to the increase of friction and interlocking of sand particle because of the reduction in paste layer between them (Hu and Wang, 2007). In other words, to attain a certain mortar flow, as the sand content increases it is necessary to increase the amount of paste to keep the distance between aggregate particles same. In mortar of low aggregate content, the effect of aggregate gradation, size and surface texture on rheology show less effect because of the high amount of paste, but this effect becomes important at high volume fraction of aggregate (Lu et al., 2008).

2.11.4 Chemical admixtures

Workability of cement based material mixes is usually improved by chemical admixtures such as, air entraining agent (AEA) and high rate water reducing admixtures (HRWRA) or super-plasticizers (SP). Air entraining agent is mainly increases paste volume to improve the mix consistency (Hu, 2005) and reduces bleeding and segregation.

Many investigators have studied the effect of admixtures on cement based materials rheology. Banfill (1991 and 1995) tested the effect of Pantarhit 45 plasticizer which based on Lingnosulphonate on mortar rheology. He reported that yield stress decreases exponentially with an increase in plasticizer concentration, but its effect on the plastic viscosity was insignificant. Similarly, Golaszewski (2006) added a polyether based super-plasticizer to mortar, he found that yield stress of mortar decreases with an increase in super-plasticizer dosage, and the increase in dosage first increased the plastic viscosity to reach a specific maximum value and then decreased. He related all these changes in rheology to the change in cement paste content in mortar, where the effect is greater when the cement paste is lower in mortar. Type of the superplasticizer also has an effect on mortar rheology. It has been found that AP- Polycarboxylate acid and AP-Polycarboxylate ester are more effective than SNF- Naphtalene Sulfonic acid, where the same dosage reduced more the yield stress of mortar. The resulted mortars using AP and PC superplasticizers had high plastic viscosity which an advantage from segregation point of view (Golaszewski and Szwabowski, 2004). In hydraulic based mortars, addition of SP results in a decrease of yield stress and no significant change in plastic viscosity (Seabra et al., 2007).

Banfill (2003) concluded that super-plasticizers can have spectacular results where sometimes unpredictable on the rheology of cement systems. He added, yield stress can be reduced to very low values by dispersion of cement particles. However, the hydration of cement causes stiffening effect which can be a serious practical problem.

2.11.5 Cement replacement materials

Additives are widely used as cement replacement materials to improve concrete or mortar fresh and hardened properties. Fly ash is the most used mineral additive because of its availability, its use in grout has improved its workability because of its particle spherical shape and smooth surface which reduce the inter-particle friction (Hu, 2005). Banfill (1991; 1993; and 1995) reported that an increase in fly ash (Safament F III) as a replacement of cement reduces both the yield stress and plastic viscosity of mortar. He noticed also, the effect of fly ash on mortar flow depends on the composition and particle size distribution, and the rounded particles of the fly ash significantly reduce both yield stress and plastic viscosity. He added, a partial replacement on volume basis has a greater effect than a replacement of the same percentage on mass basis because of the difference in cement and fly ash densities.

Khayat et al. (2008) reported that a proper replacement of cement by additives can lead to higher packing density of fine powder which reduces the inter-particle friction. They added, the spherical shape of fly ash particles enhances the flow properties when partially replaced in cement. They concluded, a partial replacement of cement by 20 or 30% fly ash in presence of superplasticizers (SP) can increase the plastic viscosity from 48 to 135 % compared with the reference grout. Similarly, Felekoglu et al (2006) used fly ash from the Soma-B thermal power plant as a cement substitution material in cement paste production and a Polycarboxylate SP. They found that the plastic viscosity has increased compared with control mix. They added, when the replacement ratio of fly ash increased no reduction has noticed even at high rotational speeds. They attributed that to the possibility of water or SP adsorption capacity of fly ash particles, and to the change in surface energy (Zeta potential) in the presence of SP. Moreover, they concluded that the effect of cement replacement materials on rheology depends on the particle shape, surface texture, size distribution and zeta potentials of the additive used. Lu (2010) reported that, in the production of self compacting concrete (SCC), when fly ash applied in the presence of SP, the SP dosage required and fly ash content are related to achieve the same flow ability. As a result, the large amount of fly ash used suggests less SP required. He reported, the fly ash works as a lubricant material and does not react with SP and results in a repulsive force, where the SP affects only on the cement.

Limestone has employed as a cement replacement material. Its effect on the rheological properties of mortar also measured. Yahia et al (2005) investigated the effect of limestone on the rheology of mortar, they found that, at given water content and polycarboxylic acid based polymer, the addition of limestone within a given range did not affect mortar fluidity, but when added beyond a critical dosage its addition resulted in a substantial increase in viscosity. They attributed that to the increase in powder concentration than the critical dosage, at which close packing of paste is reached where the free space in mortar was limited, and then, the increase in viscosity beyond this limit was expected due to the increase of inter-particle friction as a result of the increase in solid-solid contact. Svermova et al. (2002) concluded that, for certain water content and SP and viscosity agent, as the limestone percentage in grout increased the yield stress and plastic viscosity reduced.

It can be concluded that, the use of cement replacement materials in multiphase materials such as mortars results in improving the particle distribution which reduces the inter-particle friction and gives better packing density of the system. This packing can improve the particle distribution and ensure a better contribution of mixing water to achieve enough fluidity to the mixture. This brief description agrees with Svermova et al. (2002) and Yahia et al. (2005), beyond a certain percentage amount of cement replacement materials, the increase in the percentage replaced will fill the voids in the system and results in more inter-particle friction which increases the mortar viscosity.

2.11.6 Mixing

Rheology of cement paste, grout and mortar is highly affected by the mixing condition especially, mixing time, mixer efficiency, and capacity. As the duration of stirring time increases, the yield stress and plastic viscosity decrease (Tattersal and Banfill, 1983). Well mixed material leads to high structural breakdown in the mixer which results in smaller hysteresis loop area of the flow curves, the up curve and down curve are closer, and that means the material is more homogeneous during the test.

2.11.7 Elapsed time and temperature

The initial rheological parameters of mortar and their variations with time are influenced by its temperature and elapsed time (Petite et al., 2006; and Petit et al., 2007). Petit et al. (2006) reported that, the yield value changes linearly with the coupled effect of time and temperature during the dormant period for mixtures made with polynaphtalene sulfonate based super-plasticizer. They added, below a certain threshold temperature, the mortar shows a decrease in yield value over 30% of the dormant period, a sudden increase in the yield value then observed after 30%, where the yield value has increased linearly with time.

It can be concluded that, consistency of fresh based materials such as, cement paste, grout and mortar can be identified by studying their rheological properties like yield stress and plastic viscosity. A lower yield stress is preferred to lower the initial resistance of the material to flow and a lower plastic viscosity is necessary for the material to move freely with less cohesion especially for injection purposes. The effects of several factors on rheology are summarized as shown in Figure (2.12).

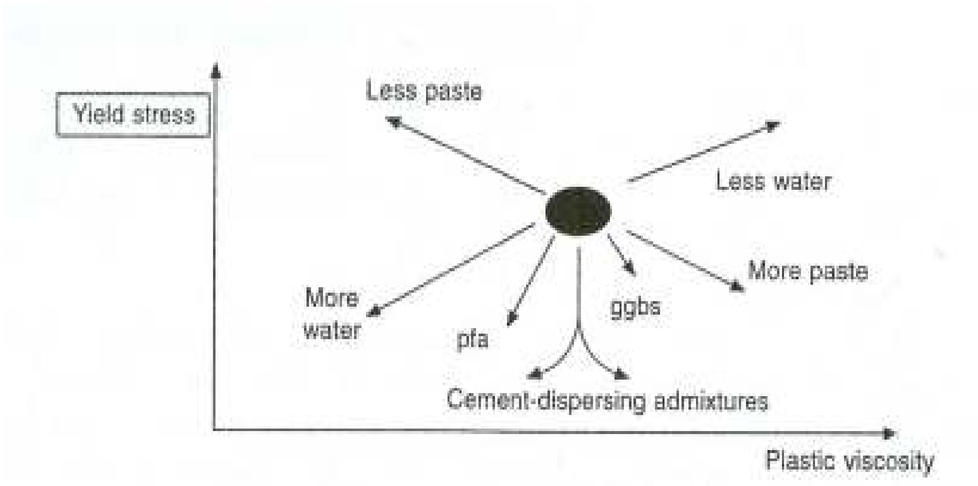


Figure 2.12 Effect of mix materials on rheology (Newman and Choo 2003)

As shown in Figure (2.12), increasing the water content decreases both rheological properties and the opposite by lowering the water content. More paste in the mix results in a decrease in yield stress and increases the plastic viscosity.

Using the super-plasticizers decreases the yield stress and slightly increases the plastic viscosity. As shown also in the figure, replacing part of the cement by fly ash decreases the yield stress and slightly decease the viscosity. Using the ground granulated blast furnace slag (ggbs) decreases grout yield stress and slightly increases the viscosity.

In conclusion, the effect of different factors on grout rheology is generally considered as a change in one factor whilst other proportions of other factors are kept constant. The combination of some factors especially the admixtures and additives is complex. Any combination of several materials should be considered for special purpose and investigated to achieve the target which they combined for.

2.12 Relative properties rheology models

Prediction of rheology of grout from its ingredients used is important from the consistency point of view. Several attempts have been done to correlate grout constituents with its rheological properties from empirical tests.

Nishibayashi et al (1996) considered the mortar as highly concentrated suspensions and the rheological constants of the mixture in terms of both the concentration of the suspensions and the properties of the suspensions and the matrix. They studied the effect of aggregate physical properties and rheological properties of paste on the rheological constants of mortar; they concluded the following relation;

$$\log\ \eta_r = -2.38 * 10^{-2}\, t_p + 1.06 \tag{2.10}$$

where, η_r is the relative viscosity of the mortar to that of cement paste and t_p is the excess paste thickness between the aggregate particles in (μ_m). In the model, viscosity of mortar depends on the viscosity of cement paste and the thickness of excess paste. More specific, excess paste thickness is the excess paste volume divided by the surface area of aggregate particles, where the excess paste volume is the remained paste after filling the voids among aggregate particles.

Murata and Kikukawa (1992) conducted a study on the relative viscosity of mortar and found that;

$$\eta_r = (1 - \frac{v}{c})^{(0.57\mu - 3.4)} \qquad (2.11)$$

where η_r is the relative viscosity of mortar to cement paste, c is the solid volume ratio of sand, v is the volumetric concentration of sand, μ is the sand fineness.

Oh et al. (1999) used the concept of relative rheological properties for self compacted concrete and reported the following equations;

$$\eta_{rc} = 0.0705\ \Gamma^{-1.69} + 1 \qquad (2.12)$$

$$\tau_{yr} = 0.0525\ \Gamma^{-2.22} + 1 \qquad (2.13)$$

where η_{rc} is the relative viscosity of concrete to mortar, τ_{yr} is the relative yield stress of concrete to mortar and Γ is the excess mortar thickness.

Ferraris and Gaidis (1992) used a parallel plate rheometer to test the effect of distance between the plates on the torque acting on the rheometer which results from the cement paste. They reported, the torque decreases as the distance between the rheometer plates increases over the range of about 0.05mm up to 0.60mm at a maximum rate of 39^{-1}s. It is noticed that the distance between the rheometer plates has a significant effect on the measured torque, especially at small distances. This result is in a good agreement with the concept of excess paste thickness which shows that as the excess paste thickness decreases both rheological properties increase.

From the models described, it can be concluded that the rheology of grout mainly affected by the distance between the solid particles and the rheology of the cement paste itself, other factors are already included for example water content will change the paste quantity and rheology, change sand quantity will be accompanied by a change in the distance between solid particles and that will change grout rheology.

2.13 Conclusions

A review on preplaced aggregate concrete production and the role of injected grout properties on the resulted concrete was presented in this chapter. The following findings are concluded:

- PAC has a high quantity of coarse aggregate reaches 70% of the total volume of concrete, there is no compaction after grout injection into the stone skeleton. The resulted concrete has contact points between the stone particles without any clearance to the grout.
- Shrinkage and creep of PAC are lower than those resulted from normal concrete because of the large amount of coarse aggregate and contact between coarse aggregate particles.
- Elastic modulus of PAC is higher than that of conventional concrete due to the huge amount of coarse aggregate and the contact between the particles.
- Grout workability or rheology is a major property in manufacturing of good quality PAC, Pozzolanic materials such as, fly ash are used as a part of cement to improve grout and concrete properties and to minimize the total cost of concrete. Admixtures like, super-plasticizers are added to the mix in order to improve the grout rheology accompanied with high quality resulted concrete.
- Grout fluidity, grout and PAC compressive strengths design equations presented from Abdelgather (1995 and 1999) investigations are not general equations however; they can be used as an approximate guidance.

- PAC compressive strength is lower than normal concrete compressive strength at early ages. In addition, compressive strengths of PAC and normal concrete are nearly the same at the age of 90 days, where the former shows higher compressive strength than the latter at the age of one year without using admixtures in the mix.
- By adding super-plasticizers and Aluminum powder to the mix, it has been reported that PAC compressive strength is higher than that resulted from normal concrete at ages of 7, 28, 90 and 365 days at the same w/c ratio.
- Grout of high sand content at low water content was too thick to penetrate the coarse aggregate voids. Consequently, the resulted concrete was honeycombed.
- By using different types (rounded, crushed and mixed) of coarse aggregate in the production of PAC; the resulted concrete exhibited different compressive strengths using the same grout compressive strength due to the difference in the interlocking between grout and coarse aggregate particles.
- PAC compressive strength was affected by the degree of grout workability. More specific, at low grout fluidity values, concrete compressive strength increases with the increase in grout workability until reaching its peak then, the compressive strength decreases with an increase in grout fluidity. First, as the grout fluidity increases more coarse aggregate voids filled with grout which results in higher compressive strength of concrete until reaching full injection at which maximum compressive strength occurs. Further grout workability results in full penetration through the coarse aggregate but because of this excess in

fluidity comes from the high water content the concrete compressive strength decreases.

- From the relation between grout fluidity and (PAC/grout) compressive strength ratio, it has been found that the ratio ranges between 0.6 – 0.8 at all grout fluidity for all mixes. Moreover, it is more likely to be concentrated around 0.70. There is an optimum in PAC-grout compressive strength ratio from fluidity.
- Viskomat NT is used to measure the rheological parameters of cement paste and mortar of particle size up to 2mm successfully. The instrument is a stress control instrument controlled by computer software. Yield stress and plastic viscosity parameters can be calculated by measuring the recorded torque at rotating speed of the blades.

From the literature presented, there are some important points are missing in the previous studies listed as follows;

- There is a wide range of missing information for comparison in the most available data in the previous studies presented by Abdelgader in his investigations like the cement replacement material used. From the used materials point of view, Awal (1985, 1988a and 1988b) used in his studies different additives and admixtures from Abdelgader (1995, 1999 and 2002). More specific, Awal used super-plasticizers of 1.25% of cement weight, aluminum powder of 1% of cement weight whereas, Abdelgader used cement with fly ash with no clear percentage and super-plasticizers at 2% of cement weight. Both Awal and Abdelgader used natural sand, with max particle size for the former of 1.18mm and the latter of 2mm, respectively.

- The effect of different sand types on the grout fluidity and on the resulted PAC properties is studied. However, effects of sand gradation on grout rheological properties in order to be injected to produce PAC are not reported.
- Effect of the change in sand type with the use of additives and admixtures and their combinations on the fresh and hardened grout properties have not included in the previous investigations and their role on the change in grout rheological properties is missing.
- There is no data available from the previous studies on the durability of PAC. Because, it has been widely used for underwater construction and massive concrete works like foundations where the high sulphat usually exist in the soil. PAC should be low permeable to protect the steel reinforcement against corrosion from the severe conditions especially in marine structures where the chlorides exist. High quality concrete is very important where the structure to be used in tidal zones to resist this harsh environment like bridge piers and dam walls. The lack of such information leading to the necessity to investigate the effect of different grout mixes on the PAC durability like sorptivity and compressive strength.

CHAPTER 3: EXCESS PASTE THICKNESS AND RHEOLOGICAL PROPERTIES OF GROUT

3.1 Introduction

In this chapter, cement paste rheology was investigated at different w/c ratios. Paste rheology was measured by the Viscomat NT. Grout was produced at different w/c ratios and c/s ratios of 1/0.9 and 1/0.6 by volume, four different types of sand were used then, grout rheology was measured using the Viskomat NT. However, Appendix B presents the experimental program for the whole study, lab work for this chapter was designed to the level of rheological tests only to investigate the effect of cement, water and sand on grout rheology without using any SP and Pfa in the mix.

The importance of studying paste rheology lies in being a part of grout and its quantity and quality has major effect on resulting grout properties (Hu, 2005). Paste quantity in grout was expressed by its excess from filling up the sand voids and separating its particles by excess paste. Paste quality was expressed by relative rheological properties by dividing grout rheology by paste rheology.

An electron microscope was used to examine the surface morphology of the sand and hence the effect of sand texture on grout rheology where rough sand surface usually results in less workability (Westerholm et al, 2007).

It is important studying different factors affecting grout rheology such as w/c, c/s ratios, sand type and quantity because all these factors affecting the grout quality and quantity which is the main part of the preplaced aggregate concrete (PAC). More specifically, grout with enough workability is necessary to be injected through the coarse aggregate to produce PAC, grout with good quality also is very important as it improves the resulting concrete.

3.2 Materials used

3.2.1 Cement

Portland cement (CEM1), grade 42.5 N was used in the production of cement paste and grout. The cement was produced by RUGBY Company. Cement density was determined using the Hosakawa Powder Densometer. Three aerated cement samples of 100 cm^3volumes were weighed and the average density of cement is obtained as 870 kg/m^3.

3.2.2 Water

School network water was used to manufacture cement paste and grout.

3.2.3 Fine aggregate

Four different types of natural sand available in the UK market were used with maximum aggregate size of 2 mm as fine aggregate (S1, S2, S3 and S4). The Hosakawa powder densometer was also used to determine sand densities. Sand properties of un-compacted densities, specific gravity and absorption were all determined. In order to find sand gradation, sand was sieved by mechanical vibrator using standard sieves.

3.2.3.1 Sand Gradation

Gradation curves of sands are shown in Figure 3.1. As shown in the figure, S2 is the finest and S1 is the coarsest. S4 is single size aggregate used as a reference.

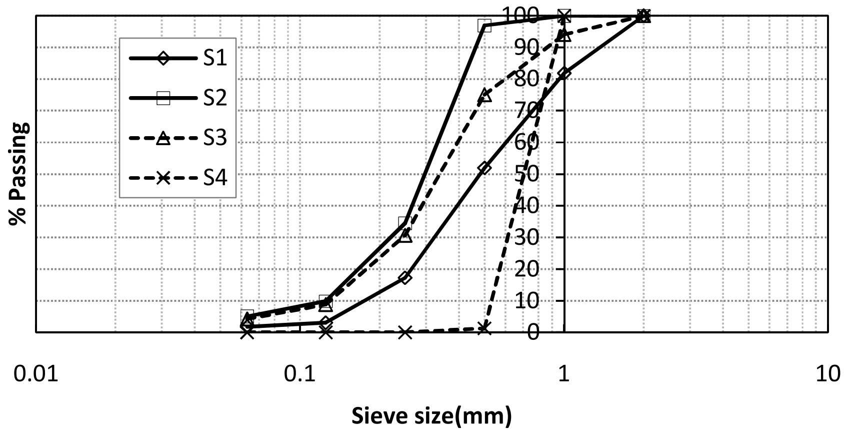


Figure 3.1 Sand gradations

3.2.3.2 Sand absorption

All sands used were oven dried at 105°C for 24 hrs in order to get an oven dry sample (BS 812-109, 1990) for grout mixing and the amount of water required for absorption was added to the water required for hydration.

Sand absorption was measured as an average of three samples by the frying pan method (Neville, 1995). In the experiment, a fully saturated sand sample of about 150 gm was heated partially in a pan with spatula stirring until the water evaporated from the surface; at the moment no sand adheres to the sides of the spatula the sand surface is deemed to be dry and its inside still saturated (SSD) (Hughes, 2008). After that, the sample was weighed and left in an oven at 105°C, after 24 hrs the sand was weighted again (OD). The absorption is determined thus:

$$\text{Absorption} = (\text{SSD} - \text{OD}) * 100 / \text{OD} \quad \% \qquad (3.1)$$

From the results shown in Table 3.1, S2 presents the highest water absorption where S4 exhibits the lowest absorption.

3.2.3.3 Sand specific gravity

Specific gravity of aggregate shown in Table 3.1 was measured by using the pycnometer; the pycnometer is a one liter jar with a watertight metal conical screw top with a small hole at the apex which can be filled with water precisely the same volume every time (Neville, 1995). The test was carried out as follows; 800 (gm) of oven dried sand was prepared, then the pycnometer filled with water and weighed as (w1), after that the pycnpmeter filled with 800 gm sand and topped with water and weighted as (w2). Specific gravity of sand can be calculated according to the following equation

$$SG = 800/(w1 - w2 + 800) \tag{3.2}$$

As shown in Table 3.1, S4 presents a slightly higher value of specific gravity than S1 and S3 where as S2 shows the lowest specific gravity.

3.2.3.4 Void ratio of sand

Void ratio of sand (V) was measured from its density and specific gravity according to the following equation

$$V = \left(1 - \frac{\gamma}{SG}\right) * 100 \tag{3.3}$$

where, ($\boldsymbol{\gamma}$) is the aerated sand density in (g/cm^3) and SG is the specific gravity of sand.

Table 3.1 shows that S2 has the highest void ratio resulting from lowest aerated density where S4 has the lowest. It is important to mention that S2 is the finest sand which resulted in highest void ratio. In addition, this is consistent with sand density as S2 has the lowest aerated density and S4 has the highest aerated density.

3.2.3.5 Sand surface area

Sand surface area was calculated by summing up the surface area of each set of known size after sieving them. Sand particle was considered as a sphere having a diameter of the average of each two successive sieves sizes. Surface area of one particle was calculated and the number of sand particles in each set was calculated according to the weight retained on a certain sieve and sand specific gravity. The surface area of each set is the number of particles multiplying by the surface area of one particle (Hu, 2005; Oh, G. 1999).

As shown in Table 3.1, S2 has the highest surface area following that S3, S1 and S4, that is in good agreement with results of sand gradation shown in Figure 3.1.

Table 3.1 Sand physical properties

Sand type	**S1**	**S2**	**S3**	**S4**
Specific gravity	2.62	2.57	2.61	2.65
Void ratio (%)	39.58	49.84	41.84	38.11
Aerated density(kg/m^3)	1583	1289	1518	1640
Absorption (%)	0.83	1.10	0.13	0.07
Specific Surface area (cm²/cm³)	175.02	313.14	268.45	81.02

3.3 Mix proportions

3.3.1 Paste

The effect of water–cement (w/c) ratio on the cement paste production was studied where w/c ratios of 0.6, 0.55, 0.50, 0.45 and 0.40 were used.

3.3.2 Grout

In order to investigate the factors influencing the rheological properties of grout, the factors studied are water-cement ratio (w/c), cement-sand ratio (c/s), fine aggregate gradation and size. Forty mixes were investigated using w/c of 0.6, 0.55, 0.50, 0.45, and 0.40, and c/s of 1/0.9, 1/0.6 using four types of sand (S1, S2, S3 and S4). The wide range of w/c ratios was used to ensure suitable workability is obtained, following to a preliminary study presented in Appendix A, the c/s ratios of 1/0.9, 1/0.6 were selected. Although c/s ratios were chosen by volume, the quantity of sand required for mixing was converted to weight according to their aerated density (Cortes D., et. al., 2008; Hu, 2005 and Hu, 2007).

3.4 Cement paste and grout mixing and testing

3.4.1 Cement paste mixing procedure

Mixing of the paste was carried out by Hobart mixer as follows. Water was put into the mixer bowl and the stop watch was started. Cement was then added to the water and the mixer was operated at low speed for two minutes. The mixer was stopped and the paste scrapped down and collected into the batch. Finally, the mixer then operated at medium speed for three minutes.

3.4.2 Grout mixing procedure

Grout was produced by mixing the constituents by Hobart mixer according to (BS EN 196-1, 2005) as follows. Water was put into the mixer bowl and the stop watch was operated. The cement was added into the bowl and the mixer was operated at low speed for 30 sec. After that, the sand was added gradually in about 30 sec during low speed mixing. The mixer was stopped after two minutes of mixing and any grout collected on the sides of the bowl was scrapped into middle of the bowel. Finally, the mixer was operated at medium speed for three minutes.

3.4.3 Cement paste and grout rheology testing

Viskomat NT is used to measure the rheological parameters of cement paste and grout. As presented in the literature, the instrument is a stress control devise controlled by computer software. Yield stress and plastic viscosity parameters of the paste, grout or mortar with max particle size of 2 mm can be calculated by measuring the recorded torque as the shear rate is increased (Scheibinger Gerate Viskomat NT, 2007).

3.5 Paste test results

Cement paste was produced at w/c ratios of 0.6, 0.55, 0.50, 0.45 and 0.40, and its rheological parameters were calculated from the relations between rotating speed and resulting torque by the material as shown in Figure 3.2. It is clear that the rheology of cement paste is affected significantly by the change of water content. Figure 3.2 shows that as the w/c ratio decreases from 0.6 to 0.4, the resulted torque increases at the same shear rate which indicates workability decreases. This is consistent with the flowability concept in which an increase of water content increases the flow of both cement paste and mortar. In addition, water increase makes the paste to become softer because of the effect on the cement particles which disperse greater at high water content. Similarly, Popovics (1982) and Hu (2005) reported that the liberation of cement particles increases by an increase in water content which leads to less yield stress and viscosity.

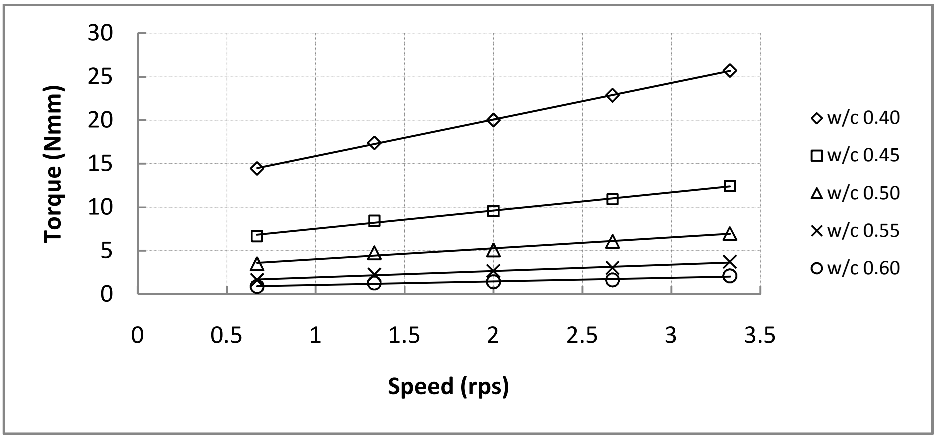


Figure 3.2 Torque vs rotating speed for cement paste at different w/c ratios

From the curves of torque *T* against speed *N* presented in Figure 3.2, the paste conforms to Bingham model presented in Equation 2.9. Figure 3.2 shows that, *g* is the intercept with the torque axis in (Nmm) and *h* is the inclination of the curves in (Nmms). Table 3.2 illustrates rheological constants of cement paste at different w/c ratios.

Table 3.2 Rheological constants of cement paste

Mix	w/c ratio	g (Nmm)	h (Nmms)
1	0.60	0.64	0.42
2	0.55	1.19	0.74
3	0.50	2.80	1.24
4	0.45	5.42	2.09
5	0.40	11.68	4.20

3.5.1 Effect of w/c ratio on the yield stress and plastic viscosity

Regression analysis was used to get the yield stress parameter (*g*) and plastic viscosity parameter (*h*) equations of cement paste as shown in Figures 3.3 and 3.4, respectively. Increasing the w/c ratio reduces both *g* and *h* exponentially for all pastes, agreeing with other studies (Banfill, 1991; Tattersal, 1991 and Hu, 2005). The reduction of *g* and *h* by increasing the water content is attributed to the liberation of cement particles and its ease to move consequently increases.

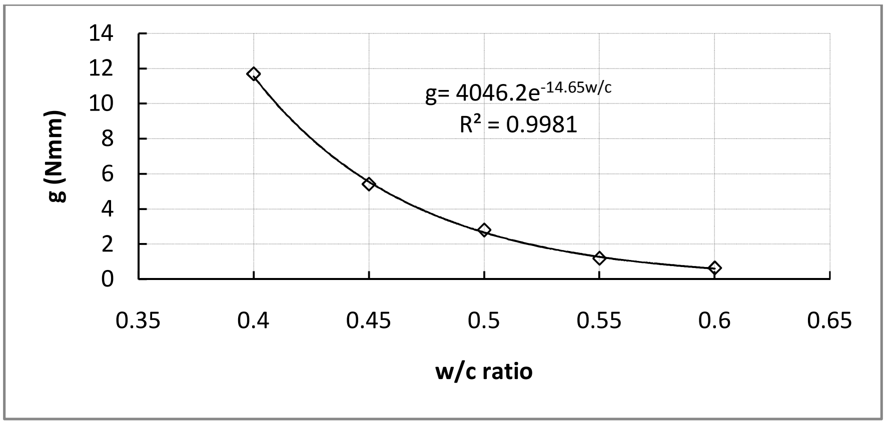


Figure 3.3 Yield stress parameter vs w/c ratio of cement paste

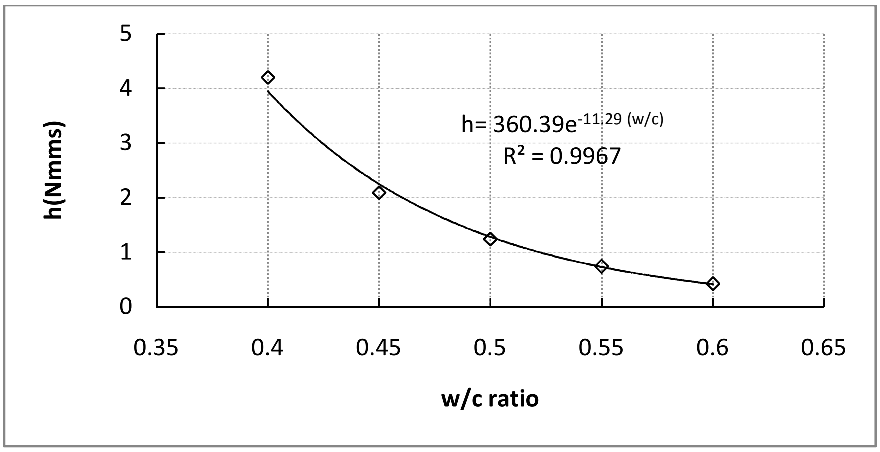


Figure 3.4 Plastic viscosity parameter vs w/c ratio of cement paste

3.6 Grout rheology test results

For a better understanding of the effect of water and sand on grout rheology, yield stress (*g*) and plastic viscosity (*h*) parameters were calculated according to Equation 2.9 and the effect of w/c on grout rheology was investigated and presented as follow.

3.6.1 Effect of w/c ratio

It is well known that mortar or cement grout workability can be increased by an increase in w/c ratio. In the production of PAC, more workable mortar is preferable and that could be achieved by an increase in w/c ratio to the limit where no bleed water will happen. The excess water traps underneath the coarse aggregate and decreases the bond between the hardened grout and coarse aggregate particles. In addition, high water content also results in segregation of fine aggregate in mortar. A wide range of w/c ratios as presented in section 3.3.2 was used in this study to achieve a wide range of workability. Rheological parameters *g* and *h* of grout were also measured by the Viskomat NT with maximum aggregate size of 2mm.

3.6.1.1 Relation between yield stress parameter and w/c ratio

In Figures 3.5 and 3.6, it is clear that in both cases of c/s ratios as the w/c ratio increases the yield stress decreases for all grouts using different sands. This relation is in agreement with others (Banfill, 1993 and Hu, 2005). The reduction in yield stress is a reflection of the reduced yield stress of paste as presented in section 3.5.1. The highest *g* value was resulted from S2 grout because of the highest force resistance and the lowest one was achieved by S4 at the same w/c ratio. The high *g* of S2 grouts is attributed to its larger void content which needs more cement paste to fill up the space between aggregate particles as reported by Hu (2005). Banfill (1994) and Westerholm et al. (2007) found that an increase of sand fineness increases both yield stress and plastic viscosity. And this can be applied on S2 which contains the highest surface area as presented in Table 3.1. On the other hand S4 shows the lowest *g* because of its low surface area and void content. S1 and S3 grouts have close *g* values in both cases of c/s ratios. Some data are missing on the graphs because some grouts were too stiff and they were not applicable to be measured by the Viskomat as shown in Table 3.3.

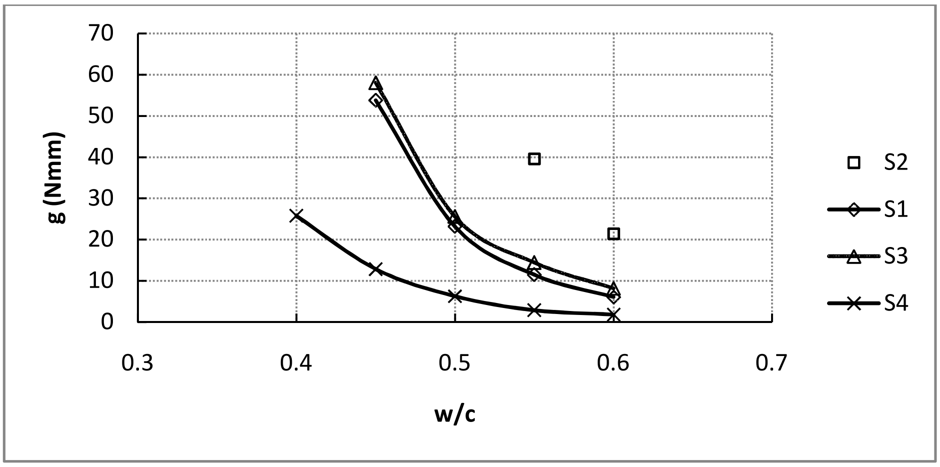


Figure 3.5 Yield stress parameter vs w/c for different sands at c/s of 1/0.9

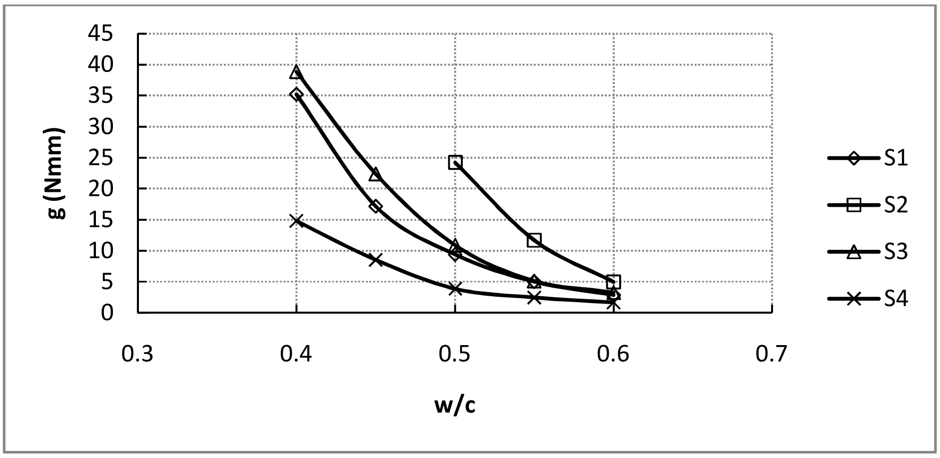


Figure 3.6 Yield stress parameter vs w/c for different sands at c/s of 1/0.6

3.6.1.2 Relation between plastic viscosity parameter and w/c ratio

Figures 3.7 and 3.8 illustrate the relations between w/c ratio and plastic viscosity parameter (*h*) for different sand grouts at c/s of 1/0.9 and 1/0.6, respectively. In both cases of c/s ratios as the w/c increases the viscosity decreases due to the increase in water content at constant cement content. Same effect was shown for cement paste in section 3.5.1, as the water content increases the viscosity of paste decreases due to the liberation of cement particles and its ease to move increases, consequently, the viscosity of grout decreases. The shown relations are in agreement with others (Jenkins et al., 1992; Banfill, 1993; and Hu, 2005). The highest *h* was produced by S2 grouts and the lowest values were resulted from S4 grouts for the same reasons as presented in yield stress section 3.6.1.1.

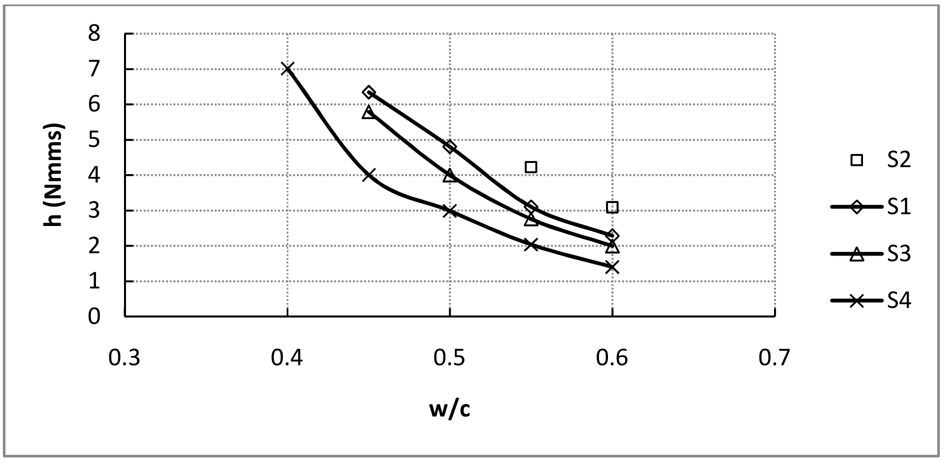


Figure 3.7 Plastic viscosity parameter vs w/c for different sands at c/s of 1/0.9

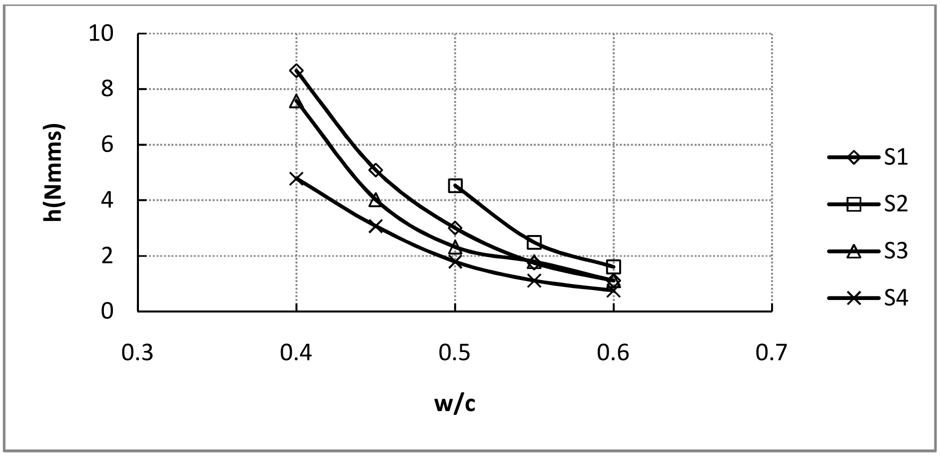


Figure 3.8 Plastic viscosity parameter vs w/c for different sands at c/s of 1/0.6

3.6.2 Effect of sand content

The effect of sand content on grout rheological properties can be seen in the comparison between c/s of 1/0.9 and c/s of 1/0.6 as presented in Table 3.3.

Table 3.3 Grout rheological parameters at different w/c and c/s ratios

Sand type	**Mix**	**w/c ratio**	***g* (Nmm)**		***h* (Nmms)**	
			c/s 1/0.9	**c/s 1/0.6**	**c/s 1/0.9**	**c/s 1/0.6**
S1	1	0.60	6.04	2.89	2.28	1.11
	2	0.55	11.44	5.89	3.1	1.75
	3	0.50	23.17	9.38	4.8	3
	4	0.45	53.75	17.17	6.34	5.09
	5	0.40	N/A	35.20	N/A	8.66
S2	1	0.60	21.46	4.97	3.09	1.60
	2	0.55	39.57	11.68	4.23	2.49
	3	0.50	N/A	24.23	N/A	4.53
	4	0.45	N/A	N/A	N/A	N/A
	5	0.40	N/A	N/A	N/A	N/A
S3	1	0.60	8.16	3.27	1.99	1.11
	2	0.55	14.41	5.14	2.76	1.79
	3	0.50	25.61	10.88	4.00	2.32
	4	0.45	58.04	22.35	5.79	4.02
	5	0.40	N/A	38.84	N/A	7.58
S4	1	0.60	1.76	1.66	1.40	0.75
	2	0.55	2.83	2.48	2.04	1.11
	3	0.50	6.26	3.87	2.99	1.79
	4	0.45	12.80	8.54	4.00	3.07
	5	0.40	25.73	14.81	7.01	4.79

It is clear that the resulted *g* and *h* at high sand content for c/s of 1/0.9 are higher than those of low sand content mixes of c/s of 1/0.6 using the same sand type at the same w/c ratio. This is attributed to the high amount of sand in the first case which increases the internal particle friction, consequently the *g* and *h* increase. Similarly, Hu (2005) reported that the increase in fine aggregate in mortar increases both yield stress and viscosity. He attributed this increase to the higher degree of friction and interlock of solid particles. Some data in Tables 3.3 are missing because grouts were too stiff and the Viskomat could not complete the test.

3.7 Relative (grout-paste) rheology and excess paste thickness

From the relations between w/c and rheological parameters presented in section 3.5, it was observed that at a certain w/c ratio, the yield stress and viscosity parameters are different for different sand grouts. Therefore, there was a need to investigate another factor which causes this change.

Nishibayashi et, al., (1996) reported that, in order to study the rheology of grout, it is advantageous to consider the mortar or grout as highly concentrated suspension where, the suspended particles are the sand particles and the matrix is the cement paste. This phenomenon is consistent with the excess paste theory presented by Kennedy (Kennedy 1940 and Oh et. al., 1999) as shown in Figure 3.9. According to the excess paste theory, the consistency of grout depends on the excess paste thickness and the paste property which is the rheology in this case.

3.7.1 Excess paste thickness

In 1940, Kennedy explained that to get concrete workability, it is necessary to have enough cement paste to cover the surface area of aggregate as shown in Figure 3.9 and excess paste to minimize the friction between aggregate particles. Moreover, as the excess paste increases the workability increases as well.

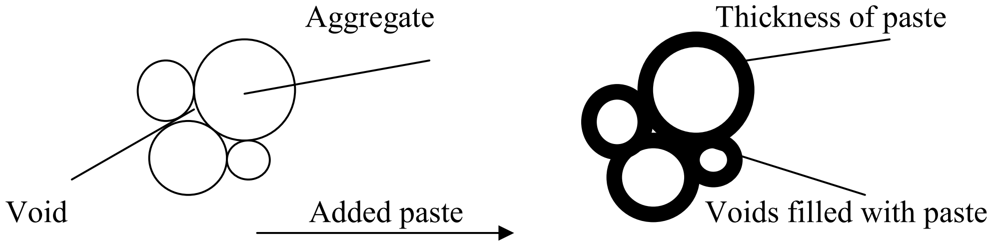


Figure 3.9 Excess paste theory

Cement paste in mortar is divided into two parts; the first part is to fill up the sand voids where the other part which called the excess paste is to coat the sand surface and to separate aggregate particles. In addition, the excess paste volume is responsible for mortar workability where a small thickness film of paste occurs between aggregate particles due to the excess paste. This film separates the sand particles and called the excess cement paste thickness (Nishibayashi et.al., 1996; Oh et. al., 1999 and Hu, 2005). In addition, as the paste thickness changes the grout workability does, in other words, rheological properties of grout changes.

Excess paste thickness can be calculated by the following equation:

$$tp = \left(1 - Vs * \frac{100}{Cs}\right) * 10^4 /(Ss * Vs) \quad (3.4)$$

where, tp is the thickness of excess paste in μm, Cs is the aerated sand solid volume percentage (%), Ss is the specific surface area of aggregate (cm^2/cm^3) and Vs is the aggregate-grout volume ratio (Nishibayashi et. al., 1996 and Oh et. al., 1999).

In the current investigation, a total number of 40 grout mixes was designed and prepared in small quantities, they were mixed by hand in polypropylene bags, care was taken not to lose any material. After 24 hours grout was taken from the bags, the volume of hardened mortar was then calculated from the difference between its weight in air and weight in water. As the sand weight was known, sand solid volume was calculated according to its specific gravity and then aggregate-mortar (Vs) volume ratio was calculated. Solid volume percentage Cs was calculated as (1- sand void ratio), and specific surface area of sands were known as shown in Table 3.1. Finally, excess paste thickness was calculated according to Equation 3.4.

Excess paste thickness also can be calculated simply by dividing the excess paste volume by the total surface area of sand (Kennedy 1940, Oh et. al., 1999).

3.7.2 Effect of excess paste thickness on the relative rheological properties

According to the program presented in section 3.3.2, a total number of 40 grout mixes was prepared then, the relationship between excess paste thickness and rheological properties was performed for the 33 mixes as shown in Figures 3.10 and 3.11. Seven mixes were not presented because they were too stiff to be measured by the Viskomat.

As shown in the figures, relative rheological constants are used; they were calculated by dividing grout rheology by paste rheology (Nishibayashi et al., 1996; Oh et. al., 1999; and Hu, 2005). Both relative rheological parameters decrease exponentially with an increase in cement paste thickness, consistent with Oh et al., (1999) and Nishibayashi et al., (1996).

Based on the presented graphs, regression analysis of data yields the following equations;

$$\text{Relative yield stress (G/g)} = 0.22 * t_p^{-1.17} \tag{3.5}$$

$$\text{Relative plastic viscosity (H/h)} = 0.679 * t_p^{-\,0.499} \tag{3.6}$$

where G and g are the yiels stress constant for grout and paste respectively (Nmm), H and h are the plastic viscosity of grout and paste respectively (Nmms), and tp is the excess paste thickness (mm).

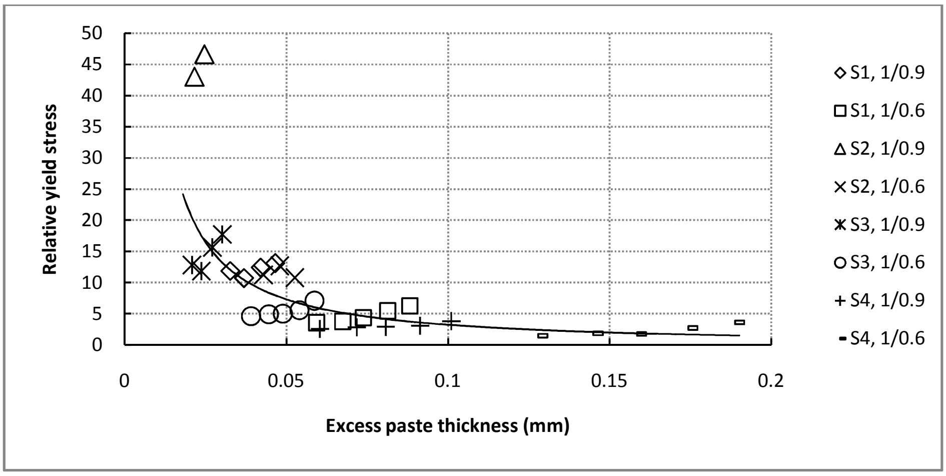


Figure 3.10 Relative yield stress vs excess paste thickness for all mixes

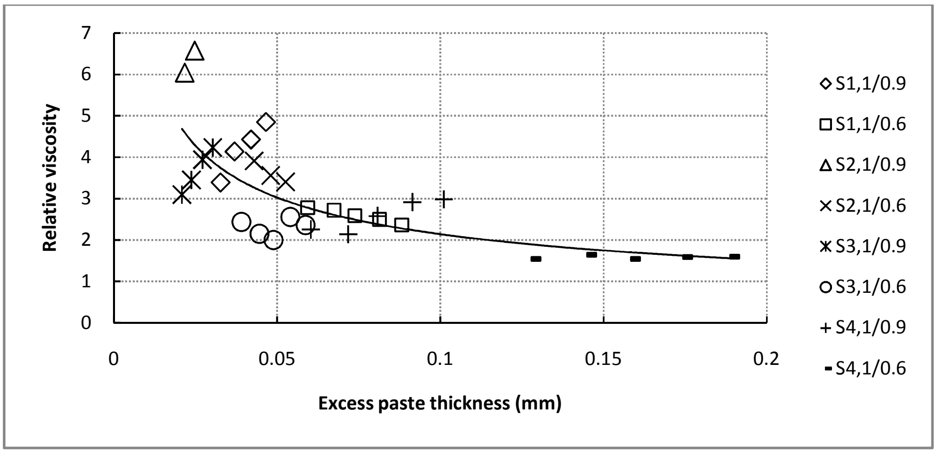


Figure 3.11 Relative plastic viscosity vs excess paste thickness for all mixes

Equation 3.6 of relative viscosity resulted from the present study was compared with Equation 2.10 presented by Nishibayashi et al., (1996) as shown in Figure 3.12. Although, Nishibayashi et al. (1996) have underestimated the relative viscosity at high excess paste thickness to the level of nearly zero which may limit the range of the applicability of this relation, the same trend between their data and the present investigation is observed. Moreover, the lower values of Nishibayashi et al. (1996) of relative viscosity at the same excess paste thickness especially at high thickness is attributed to the effect of the superplasticizer used where the excess paste volume may contain air voids, and the difference is attributed to the difference in cement paste viscosity.

Due to the lack of information in the literature on the relative yield shear equations, grout yield stress Equation 3.5 cannot be compared.

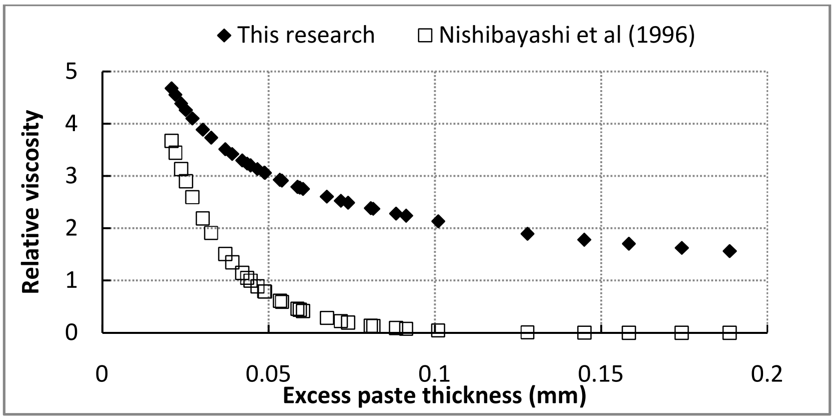


Figure 3.12 Comparison between different relative viscosity equations

Although the trends in Figures 3.10 and 3.11 show that both relative yield stress and plastic viscosity decrease with the increase in excess paste thickness, it seems that for a given sand type and c/s ratio the relative yield stress decrease with a decrease in *tp*. Similarly, relative plastic viscosity at c/s of 1/0.9 decreases with adecrease in *tp*. This led to check if there is any better relation between the rheological parameters for grout and paste and the excess paste thickness. For this purpose, a non linear statistical regression analysis was performed for the expermintal data using Excel solver 2007. Linear regression using the logarithm values of the input and output parameters were used because the significance analysis can only be performed generally in linear regression which is not applicable in these relations (Hu, 2005; Kleinbaum et al. 1998). Non linear relations between grout and paste rheological parameters and excess paste thickness were resulted as shown in equations 3.7 and 3.8. The relations are statistically significant with correlation coeffiecients (R^2) of 0.93 and 0.90 for yield stress and plastic viscosity equations, respectively.

$$G = 0.27 * g^{0.63} * t_p^{-1.17} \tag{3.7}$$

$$H = 0.68 * h^{0.78} * t_p^{-0.50} \tag{3.8}$$

Where G and g are the yiels stress constant for grout and paste respectively (Nmm),

H and h are the plastic viscosity of grout and paste respectively (Nmms) and

t_p is the excess paste thickness (mm)

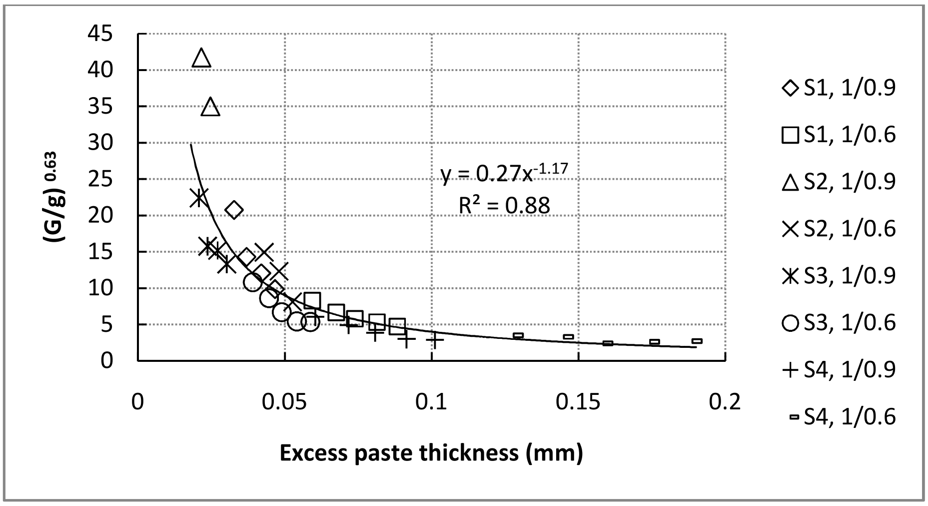


Figure 3.13 $(G/g)^{0.63}$ vs excess paste thickness for all mixes

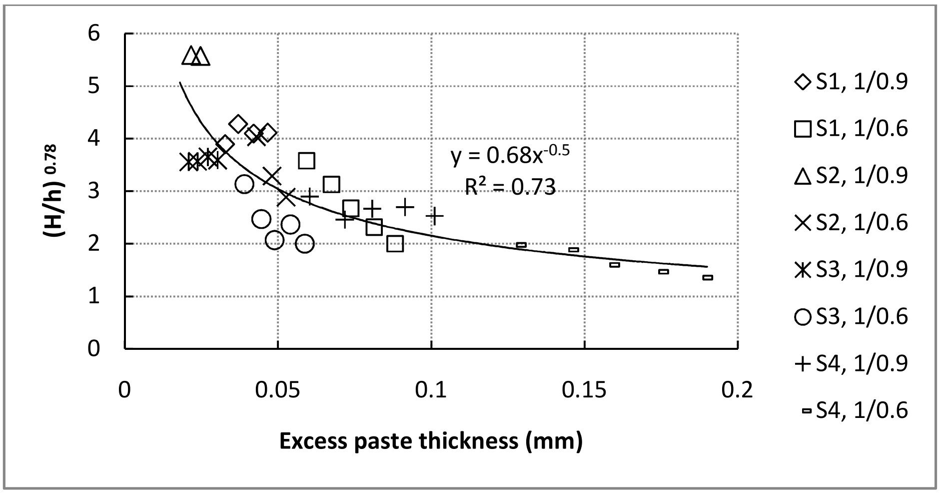
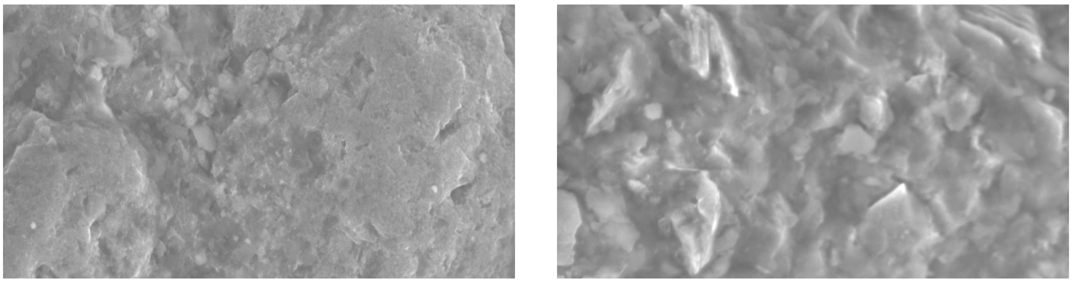


Figure 3.14 $(H/h)^{0.78}$ vs excess paste thickness for all mixes

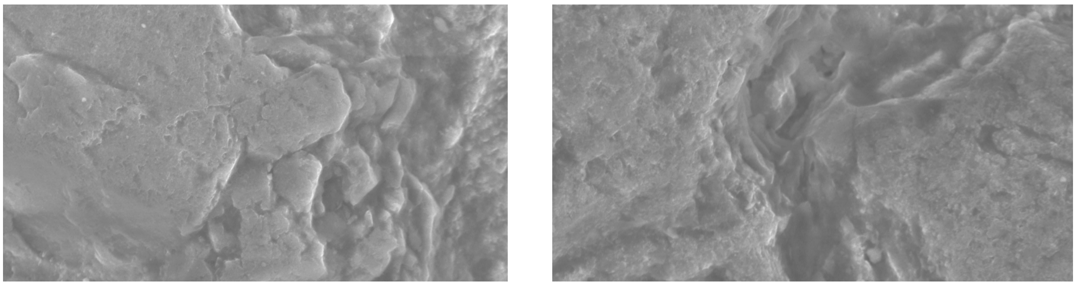
Figures 3.13 and 3.14 show that relative performane decrease with the increase in excess paste thickness. A better trends were found than presented in Figures 3.10 and 3.11 with cement paste powers of 0.63 and 0.78 for yield stress and viscosity, respectively. The trends show that the relations are applicable for all sands at different c/s ratios. Although the improvement in the yield stress trend of a certain sand grout is clear, a little difference in plastic viscosity was observed. Fairly speaking, for simplicity, the general picture in the relation between relative rheological performance and excess paste thickness can be considered as presented in equations 3.5 and 3.6.

The most significant finding from this presentation is that S2 grouts at c/s of 1/0.9 show the highest relative properties at very low paste thickness for two mixes of w/c of 0.60 and 0.55; other w/c ratios were too stiff to be measured by the Viskomat. Since some mixes have the same excess paste thickness with lower relative performance which means that the effect has not come from the high sand surface area. Consequently, sand surface was scanned by electron microscope in order to investigate the effect of sand texture on mortar rheology as shown in Figure 3.15.

In the scanning test S1, S2 and S3 were sieved and particles passed through 0.25mm and retained on 0.125mm were collected and scanned. Since S4 is a single size sand, only particles retained on sieve 0.5mm were scanned. As shown in Figure 3.15-b, S2 differs from others, its surface is very rough and contains many edges which increase the interlocking of particles and friction between them decreasing mortar workability at low cement paste content. Other sands show smooth surfaces and some even show pitting.



(a) S1, sand size of 0.125 mm (b) S2, sand size of 0.125 mm



(c) S3, sand size of 0.125 mm (d) S4, sand size of 0.50 mm

Figure 3.15 Sand surface magnifications of 1000 times

3.8 Conclusions

A study on the effect of different types of fine aggregate and cement paste on grout rheological properties was experimentally investigated. The relations between different factors were also presented and the following conclusions may be drawn:

- Grout rheology is mainly affected by the water content where the rhelogical properties decrease with an increase in w/c ratio. Moreover, fine aggregate properties and contents are also affecting the grout behavior.
- Grout yield stress and viscosity increase with the increase in sand content at the same w/c ratio for the same sand type because of the increase in sand surface area.

- As the sand surface area increases more paste is needed to cover its surface to attain certain workability. If the paste volume is constant then, the resulted rheological parameters are controlled by the surface area of sand.
- The amount of cement paste required for mortar workability is divided into two parts. The first part is the paste required to fill up sand voids where the other part is to separate aggregate particles by the excess paste layer to minimize friction between aggregate particles as presented in section 3.7.1.
- Rheology of grout can be identified by two factors; the rheology of cement paste and the excess paste thickness which results from filling up sand voids and covering its surface.
- Grout-paste rheological properties increase with the decrease in cement paste thickness to very low values until the sand surface roughness becomes very important due to the high friction of sand particles.
- Relative viscosity model resulted from this research was compared with other studies and proved its validity where relative yield stress was not compared due the lack of such information for mortar in the literature.
- Sand surface texture can be considered as an important property especially at low excess paste thickness in grout, as it affects grout injection in the production of PAC. Consequently, very low values of cement paste thickness should be avoided in the grout design for PAC.

CHAPTER 4: FRESH PROPERTIES OF GROUT WITH ADDITIVES AND ADMIXTURES.

4.1 Introduction

An investigation on the effect of different grout ingredients on its rheology is presented in this chapter because of the importance of grout in the production of PAC. The effect of different sand properties on grout fresh properties was investigated in chapter three without using any chemical and mineral additives. This chapter aims to study the effect of different materials on grout fresh properties with and without chemical and mineral additives as presented in Appendix B.

Grouts presented in this chapter were designed to define the degree of workability which makes the grout be able to penetrate through the coarse aggregate and produces PAC with less bleeding rates. In addition, the threshold of the grout injection rheology through the coarse aggregate was defined using different materials, and that will be presented in chapter 5.

Grouts were first produced without any admixtures and additives, then superplasticizer (SP) of 2% and 1% was added and grout rheology was tested. Finally, SP percentage of 1% was fixed and pulverised fly ash (Pfa) was employed as a cement replacement material at 20% by weight according to the experimental program shown in Appendix B. There is no hardened grout and hardened PAC produced in chapters 4 and 5.

4.2 Used materials

In addition to the materials used in the experiments presented in chapter three for producing paste and mortar, chemical admixture and cement replacement materials were used in the production of grout to improve its performance, they are shown below

4.2.1Pulverised fuel ash

Additive used in the study for grout in order to produce PAC as a cement replacement material was a Pulverised fuel ash from Drax, Yorkshire; its loss on ignition (LOI) is 7% which satisfies the requirements of the British standard BS 3892 (1993). The required quantities for all work were delivered in one package in sealed containers.

4.2.2 Superplastisizers

Glenium C315 Super-plasticizers (SP) was ordered from BASF. CC. UK. LTD. This product is a third generation superplasticizer based on modified polycarboxylic ether, and also complies with EN 934 part 2 and is compatible with all types of cement (BASF, 2010).

4.3 Rheology tests

Viskomat NT was used to measure the rheological parameters, yield stress (*g*) and plastic viscosity (*h*) of cement paste and grout. In addition to the Viskomat NT, three more tests were elaborated in order to get a full assessment for the grouts rheology; flow cone, colcrete flow meter as presented in section 2.10 and bleeding tests.

4.3.1 Modified flow meter test

Since the grout used in PAC production has to be high flowability, colcrete flow meter channel length of 700 mm presented in section 2.10.1.3 was not sufficient to measure the grout fluidity. Consequently, to overcome the limitation of the channel length, the time required for the grout to reach a certain distance through the channel was recorded, then for each grout the speed was calculated in cm/sec. By this modification high flow grouts could be tested and relatively stiff grouts which did not penetrate through the flow cone also tested.

4.3.2 Grout bleeding test

The importance of the test is to measure the amount of excess water in grout which can adversely affect on concrete strength, and that can be achieved by measuring the amount of bleed water at the grout surface. The grout is poured in quantities of about 800±10 ml into 1000 ml graduated cylinder. The first grout level is the first volume reading and the final reading is taken at 3 hours as the volume of bleed water (ASTM C 940-89).

$$\text{Final bleeding \%}= \frac{volume\ of\ bleed\ water}{first\ volume} * 100 \tag{4.1}$$

4.4 Effect of w/c ratio on the rheology of paste

In addition to the paste presented in Figure 3.4 for non admixture mixes, superplastisizer (SP) at 1% and 2% of the weight of cement was employed in the production of cement paste at w/c of 0.3 to 0.6 and compared as shown in Figure 4.1. The effect of w/c ratio on the paste rheology was investigated in order to understand the effect of paste rheology on grouts. As shown in Figure 4.1 h increases exponentially with the decrease in w/c ratio, agreeing well with other investigations (Tattersall 1991; Wallevik and Wallevik 1998; and Hu 2005). It is also shown that at a constant w/c ratio, paste with SP shows less h values than that without SP, the values of h for grouts of 1% and 2% SP at constant w/c ratio are similar except at w/c of 0.3. Due to the effect of SP, paste *g* values are zero and only *h* values of cement paste could be calculated.

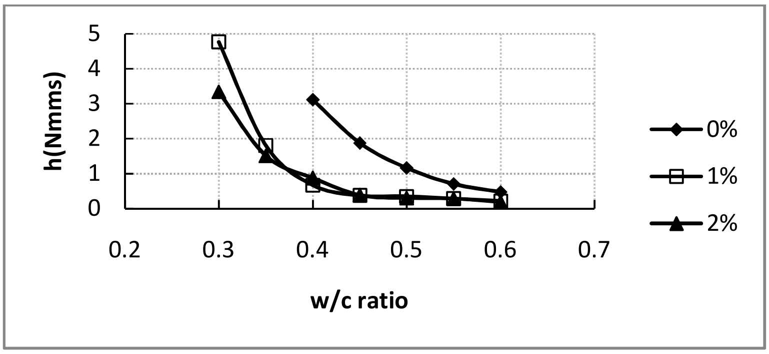


Figure 4.1 Paste plastic viscosity vs w/c ratio at different SP ratios

4.5 Rheology of grout

Grout rheology measurements were carried out by Viskomat NT, flow cone, and modified flow meter for grouts with and without additives and admixtures using different sand types. The effect of different parameters such as, w/c ratio, c/s ratio SP percentage and Pfa on grout rheology has been investigated and the results from this work are shown below.

4.5.1. Effect of w/c ratio on the rheology for non admixture mixes

As shown in Figures 4.2 and 4.3, *g* value of grout decreases with an increase in water content at c/s of 1/0.9 and 1/0.6, respectively. S4 grouts show lower values because of its low surface area and spherical shape. On the other hand, S2 grouts resulted in higher *g* because of its rough shape and higher surface area. S3 and S4 grouts illustrate closer values in both cases of sand content. Some data are missing at c/s of 1/0.9 because the grouts were too stiff to be tested by the Viskomat. Lower sand content grouts at c/s of

1/0.6 resulted in lower *g* for all grouts comparing with those of c/s of 1/0.9. In both cases of sand contents, S2 grouts show higher values than other sands because of its higher surface area which needs more paste to cover its surface. In addition to the data in Table 4.1, some rheology data shown on the graphs were presented in Table 3.3. Flow cone test results show that grouts of high yield stress are not applicable to be measured by the flow cone. The flow will not occur because the pressure gradient created by the grout weight in the funnel is not sufficient for the shear stress to overcome the yield stress in the nozzle (Roussel and Le Roy, 2005).

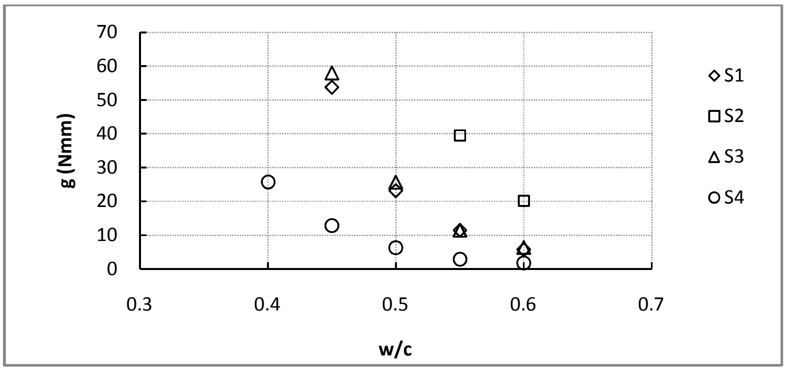


Figure 4.2 Grout yield stress vs w/c ratio at c/s of 1/0.9

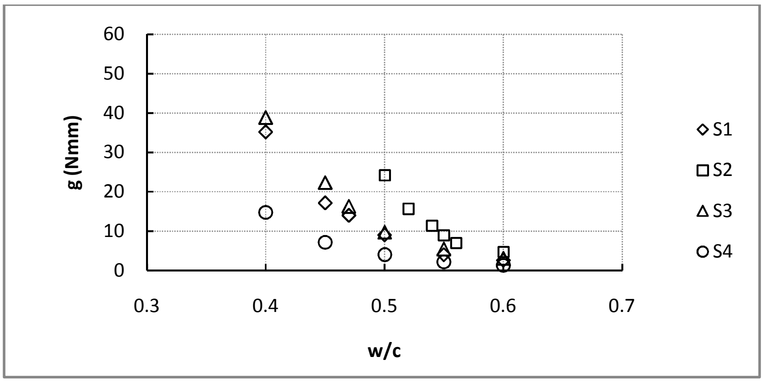


Figure 4.3 Grout yield stress vs w/c ratio at s/c of 1/0.6

Table 4.1 Rheology test results for non admixture grouts

Mix No.	**Sand type**	**c/s ratio**	**w/c ratio**	***g* (Nmm)**	***h* (Nmms)**	**Flow time (sec)**	**Bleeding (%)**
1	S1	1/0.9	0.60	5.73	2.37	36	1.90
2	S1	1/0.9	0.55	11.44	3.10	N/A	0.50
3	S1	1/0.6	0.60	2.63	1.34	17	12.80
4	S1	1/0.6	0.55	4.01	1.92	25	7.80
5	S1	1/0.6	0.50	9.47	2.94	70	1.00
6	S1	1/0.6	0.49	9.61	3.36	N/A	0.60
7	S1	1/0.6	0.48	11.82	3.65	N/A	0.20
8	S1	1/0.6	0.47	14.91	3.58	N/A	0.40
9	S2	1/0.9	0.60	20.24	3.1	N/A	0
10	S2	1/0.6	0.60	4.77	1.36	25	11.60
11	S2	1/0.6	0.56	7.07	1.92	65	1.20
12	S2	1/0.6	0.55	8.96	2.16	N/A	0.90
13	S2	1/0.6	0.54	11.43	2.18	N/A	0.60
14	S2	1/0.6	0.52	15.65	3.14	N/A	0.40
15	S2	1/0.6	0.50	24.23	4.53	N/A	1.00
16	S3	1/0.9	0.60	6.39	1.80	45	5.00
17	S3	1/0.9	0.55	11.42	2.75	N/A	0.40
18	S3	1/0.6	0.60	3.09	1.10	18	12.00
19	S3	1/0.6	0.55	5.46	1.68	27	6.00
20	S3	1/0.6	0.50	9.75	2.33	N/A	1.00
21	S3	1/0.6	0.47	16.29	3.39	N/A	0.60
22	S4	1/0.9	0.60	1.76	1.40	24	7.00
23	S4	1/0.9	0.55	2.83	2.04	N/A	5.00
24	S4	1/0.9	0.50	6.26	2.99	18	1.00
25	S4	1/0.6	0.60	1.35	0.68	13	19.00
26	S4	1/0.6	0.55	2.23	1.16	17	15.00
27	S4	1/0.6	0.50	4.04	2.30	26	5.00
28	S4	1/0.6	0.45	7.23	2.98	N/A	0.60
29	S4	1/0.6	0.40	14.81	4.79	N/A	0.10

Figures 4.4 and 4.5 show that grout *h* values decrease with an increase in water content. As in case of yield stress S2 in grout resulted in the highest values of *h* than other sands which is attributed to its high surface area and rough shape. In contrast to that, S4 resulted in the lowest *h* because of its rounded shape and lowest surface area. S1 and S3 have approximately same *h* especially at high w/c ratios. Lower sand content, c/s of 1/0.6 resulted in low *h* for all grouts than those resulted from c/s of 1/0.9 and that is attributed to the low sand content at constant cement paste content. In other words, the high sand content at c/s of 1/0.9 decreases the excess paste thickness; as a result the plastic viscosity *h* increases. This is in good agreement with Hu (2005). A decrease of maximum aggregate size also increases the water demand and of course decreases mortar and concrete workability (Mehta, 1986). The decrease of maximum aggregate size increases the surface area of aggregate which needs more water to increase the volume of paste to keep the workability constant, and because the paste kept constant higher friction between aggregate particles results in lower workability. The higher quantity of sand at c/s of 1/0.9 in grouts resulted in higher *g* and *h* compared with c/s ratio 1/0.6 grouts as presented in Table 4.1.

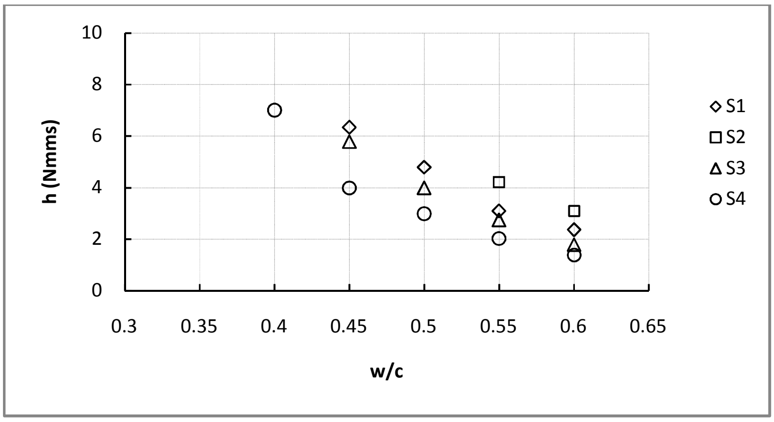


Figure 4.4 Plastic viscosity of grout vs w/c ratio at c/s of 1/0.9

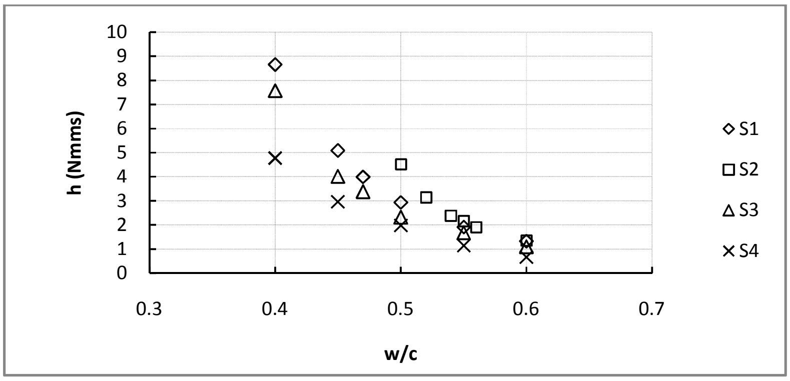


Figure 4.5 Plastic viscosity of grout vs w/c ratio at c/s of 1/0.6

4.5.2 Effect of w/c ratio on the rheology for 2% SP grouts.

The effect of w/c ratio on the grout yield stress of grouts with 2% SP at c/s of 1/0.9 and 1/0.6 are shown in Figures 4.6 and 4.7, respectively. Due to the effect of SP on *g* values, there is a large scatter points and there is no consistent trend of data. This is attributed to an instrumental error in measuring yield stress even at high sand contents at c/s of 1/0.9 as presented in Figure 4.6. Sand segregation was noticed in the Viskomat bowl during the experiment which resulted in higher values of *g*. In other words, segregation effect makes the sand precipitates to the bottom of the Viskomat bowl during the test and gives higher yield stress values at higher water content due to the combined effect of high water content and SP. It is important to mention that, before the Viskomat operated, the grout was stirred in its bowl by spatula to avoid any sedimentation of sand due to the vibration of grout, which occured during walking between the grout mixer and the Viskomat room. Some grouts of zero *g* values were recorded due to the effect of SP for c/s of 1/0.9 grouts. Figure 4.7 shows that most of the grouts resulted in zero *g* values at c/s of 1/0.6 due to self levelling behaviour agreeing with Bager et al. (2001), Huang (2001) and Yahia and Khayat (2001) for self levelling grouts. As a result there was no reliable data in yield stress considered because of high segregation resulted from the effect of high SP dosage.

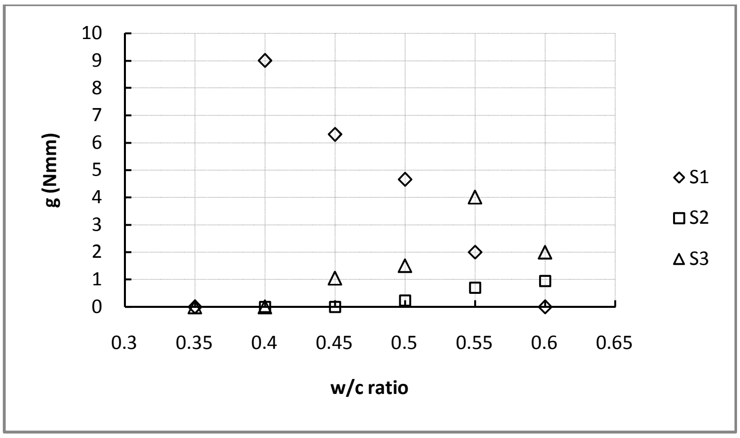


Figure 4.6 Grout yield stress vs w/c ratio at c/s of 1/0.9 with 2% SP

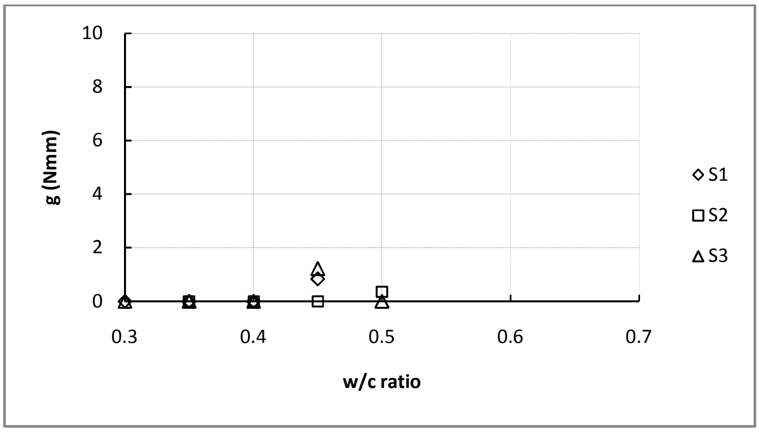


Figure 4.7 Grout yield stress vs w/c ratio at c/s of 1/0.6 with 2% SP

Table 4.2 Rheology test results for grouts of 2% SP

Mix No.	**Sand type**	**c/s ratio**	**w/c ratio**	***g* (Nmm)**	***h* (Nmms)**	**Flow time**	**Bleeding (%)**	**Flow speed**
1	S1	1/0.9	0.60	0	0.97	14	10.60	-
2	S1	1/0.9	0.55	2	0.41	24	8.70	-
3	S1	1/0.9	0.50	4.66	0.14	33	7.50	-
4	S1	1/0.9	0.45	6.30	1.35	59	6.20	-
5	S1	1/0.9	0.40	9.00	9.49	129	2.50	-
6	S1	1/0.9	0.35	0	44.86	159	1.20	1.83
7	S1	1/0.6	0.50	-	-	20	16.20	37.04
8	S1	1/0.6	0.45	0.83	0.79	26	7.50	21.28
9	S1	1/0.6	0.40	0	6.51	96	3.10	12.50
10	S1	1/0.6	0.35	0	12.61	116	0	9.10
11	S1	1/0.6	0.30	0	36.21	N/A	0	3.40
12	S2	1/0.9	0.60	0.95	0.59	17	11.20	-
13	S2	1/0.9	0.55	0.71	1.41	26	10.00	-
14	S2	1/0.9	0.50	0.24	2.95	43	7.50	-
15	S2	1/0.9	0.45	0	6.50	98	1.90	-
16	S2	1/0.9	0.40	0	12.61	N/A	0	-
17	S2	1/0.6	0.50	0.36	0.80	21	15.60	30.86
18	S2	1/0.6	0.45	0	1.97	34	11.90	20.00
19	S2	1/0.6	0.40	0	3.68	76	6.20	14.53
20	S2	1/0.6	0.35	0	15.35	N/A	0.60	4.06
21	S3	1/0.9	0.60	2	0.31	18	12.50	-
22	S3	1/0.9	0.55	4.01	0.30	23	11.20	-
23	S3	1/0.9	0.50	1.51	0.75	29	10.60	-
24	S3	1/0.9	0.45	1.05	3.76	72	6.20	-
25	S3	1/0.9	0.40	0	9.45	130	0.60	-
26	S3	1/0.9	0.35	0	17.42	179	0.60	4.60
27	S3	1/0.6	0.50	0	0.1	19.63	13.10	34.01
28	S3	1/0.6	0.45	1.22	4.92	30.65	16.20	21.64
29	S3	1/0.6	0.40	0	5.35	50	6.90	17.36
30	S3	1/0.6	0.35	0	11.53	116	0.60	8.00
31	S3	1/0.6	0.30	0	27.37	N/A	0	2.44

Figures 4.8 and 4.9 show the effect of w/c ratio on the plastic viscosity of grouts with 2% SP at c/s 1/0.9 and 1/0.6, respectively. In both cases of c/s ratios, *h* exponentially decreases with the increase in w/c ratio. It is interesting to notice that all grouts show closer *h* values indicating that the effect of sand type has disappeared due to the high dosage of SP in both cases of c/s ratios. This conclusion was noticed by Nowek et al. (2007). They reported that the effect of sand of maximum sizes of 1mm and 2mm on fluidity is minimized by using SP. Moreover, the same result was reported by Abdelgader (1996) when he noticed that sand gradation has no effect on grout workability. Although he did not explained why, the reason was the high amount of 2% SP he used with sands of maximum sizes of 1 mm and 2mm.

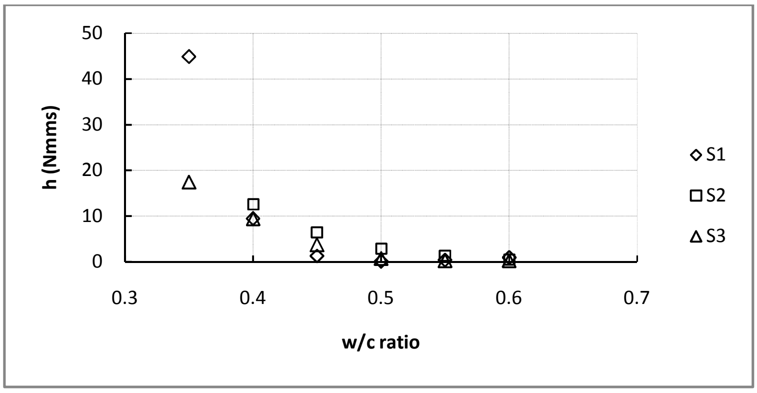


Figure 4.8 Grout plastic viscosity vs w/c ratio at c/s of 1/0.9 with 2% SP

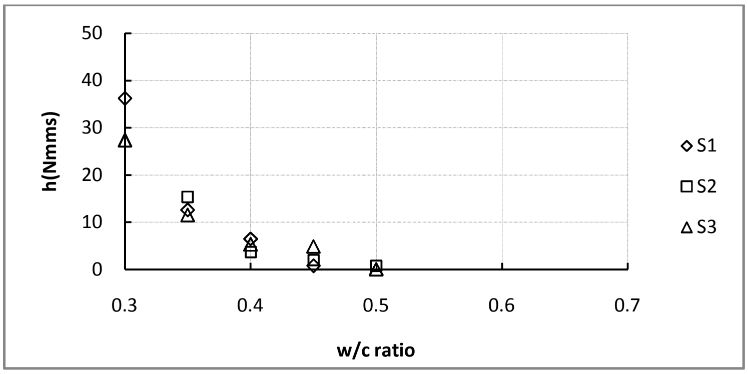


Figure 4.9 Grout plastic viscosity vs w/c ratio at c/s of 1/0.6 with 2% SP

4.5.3 Effect of w/c ratio on the rheology for 1% SP grouts

The effect of w/c ratio on the grout yield stress of mixes with 1% SP at c/s of 1/0.9 and 1/0.6 are shown in Figures 4.10 and 4.11, respectively. However, SP dosage has adjusted from 2% to 1% there is still large scatter points with no consistent trend of data especially at w/c ratios 0.45 to 0.50 as presented in Figure 4.10 for S1 grouts. Sand segregation was noticed in the Viskomat bowl during the experiment. Some grouts of zero *g* values were recorded due to the effect of SP for both cases of c/s ratios as presented in Figures 4.10 and 4.11, concluding that less interparticle friction resulted between sand particles.

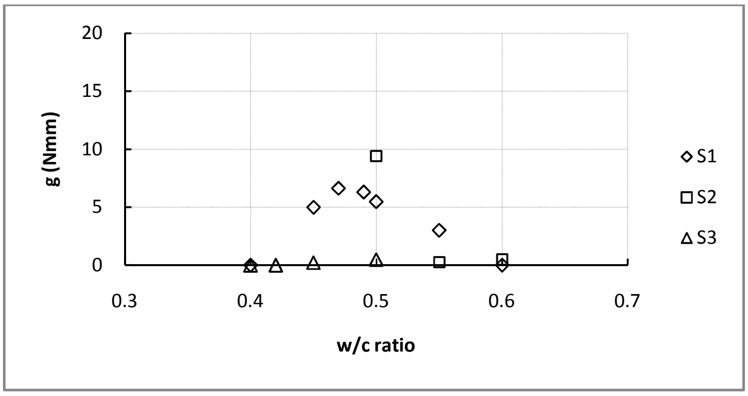


Figure 4.10 Grout yield stress vs w/c ratio at c/s of 1/0.9 with 1% SP

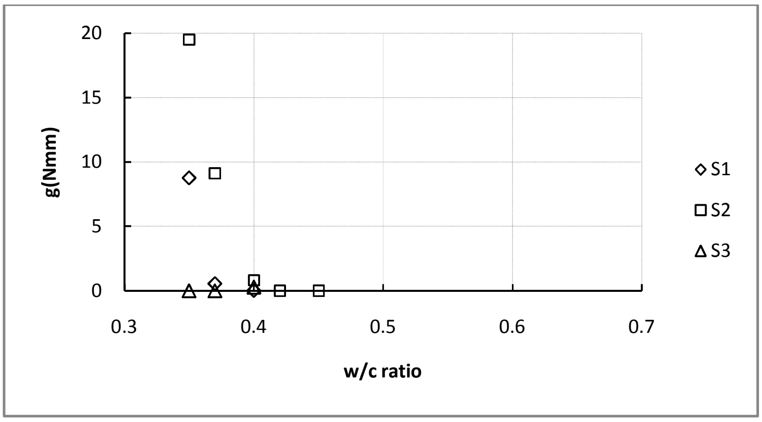


Figure 4.11Grout yield stress vs w/c ratio at c/s of 1/0.6 with 1% SP

Table 4.3 Rheology test results for grouts of 1% SP

Mix No.	**Sand type**	**c/s ratio**	**w/c ratio**	***g* (Nmm)**	***h* (Nmms)**	**Flow time**	**Bleeding (%)**	**Flow speed**
1	S1	1/0.9	0.60	-	-	15	3.70	32.68
2	S1	1/0.9	0.55	3.00	0.50	22	2.50	22.52
3	S1	1/0.9	0.50	5.48	1.00	35	1.50	15.87
4	S1	1/0.9	0.49	6.30	1.91	46	3.10	11.68
5	S1	1/0.9	0.47	6.63	4.03	55	1.20	11.11
6	S1	1/0.9	0.45	5.00	4.94	70	0.90	10.20
7	S1	1/0.9	0.40	0	12.61	130	0	0
8	S1	1/0.6	0.40	0.04	4.4	61	0.60	11.21
9	S1	1/0.6	0.37	0.57	5.81	71	0.60	8.88
10	S1	1/0.6	0.35	8.77	9.57	124	0	4.46
11	S2	1/0.9	0.60	0.48	0.91	18	4.40	30.12
12	S2	1/0.9	0.55	0.28	2.16	31	3.10	19.01
13	S2	1/0.9	0.50	9.42	5.80	91	0.60	5.02
14	S2	1/0.6	0.45	0	2.51	41	2.10	19.23
15	S2	1/0.6	0.42	0	4.11	68	1.90	10.27
16	S2	1/0.6	0.40	0.83	5.17	75	0.60	8.53
17	S2	1/0.6	0.37	9.14	12.62	180	0.10	1.43
18	S2	1/0.6	0.35	19.52	21.66	N/A	0.10	0.85
19	S3	1/0.9	0.50	0	2.09	35	2.50	17.42
20	S3	1/0.9	0.45	0.23	5.01	66	1.20	8.00
21	S3	1/0.9	0.42	0	8.77	120	0	3.77
22	S3	1/0.9	0.40	0	11.44	180	0	2.75
23	S3	1/0.6	0.40	0.3	3.34	52	0.60	12.82
24	S3	1/0.6	0.37	0	6.14	85	0.60	6.72
25	S3	1/0.6	0.35	0	8.54	117	0	6.33

Figures 4.12 and 4.13 demonstrate the effect of w/c ratio on the plastic viscosity of grouts at c/s 1/0.9 and 1/0.6, respectively. In both cases of c/s ratios, *h* exponentially decreases with the increase in w/c ratio. S2 grouts exhibit higher *h* values than other sand grouts, where S1 and S3 show the same results. Using c/s of 1/0.9 resulted in higher *h* values than c/s of 1/0.6 at the same w/c ratios. The higher quantity of sand at c/s of 1/0.9 in grouts resulted in higher *h* compared with c/s ratio 1/0.6 grouts as presented in Table 4.3. W/c ratios used at c/s of 1/0.9 are not the same as that used at c/s of 1/0.6 because the purpose of this choice was to get an inject-able grout through the coarse aggregate to produce PAC.

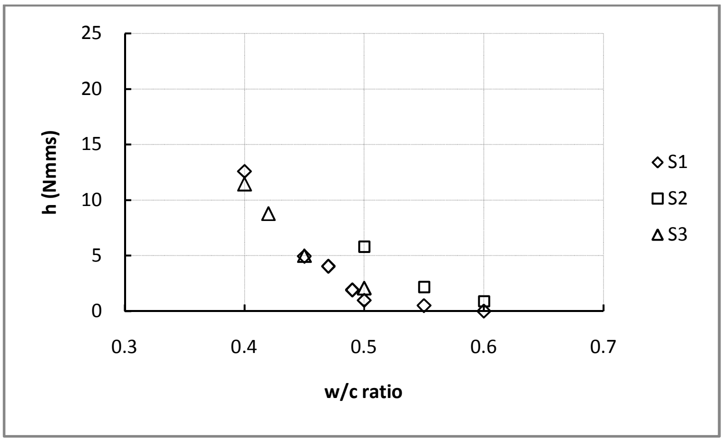


Figure 4.12 Grout plastic viscosity vs w/c ratio at c/s of 1/0.9 with 1% SP

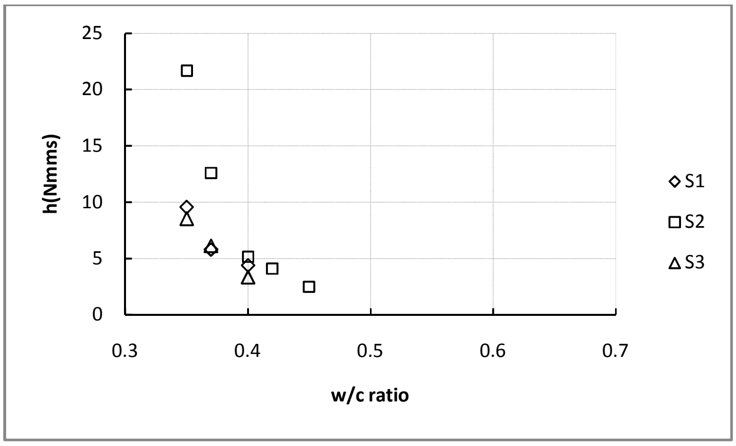


Figure 4.13 Grout plastic viscosity vs w/c ratio at c/s of 1/0.6 with 1% SP

4.5.4 Effect of w/c ratio on the rheology for 1% SP and 20% Pfa grouts.

Pfa was employed with the addition of superplasticizers at dosage of 2% in the grout production, and then it was successfully injected into the coarse aggregate and good quality PAC was produced (Abdelgader, 1995 and 1996). Pfa was also employed with the use of high dosage of superplasticizer at very low water content in the production of wet-mix sprayed concrete; the resulted concrete had good volume stability, good freeze/thaw durability and very low chloride permeability (Austin and Robins, 1995).

Liu (2010) reported that SP percentage in self compacting concrete (SCC) decreases with an increase in fly ash content up to 39%. It was suggested to use only 1% SP and investigate the effect of Pfa on grout rheology. Fly ash of 20% of cement weight was employed in self consolidated mortars by Sonebi (2001), and Rizwan and Bier (2009 and 2012). Moreover 20 % was chosen because a smaller amount has an optimum efficiency and gives a large increase in compressive strength where a large amount has less effect as reported by Cyr et al. (2006).

The effect of w/c ratio on yield stress of grouts contain 1% SP and 20% Pfa at c/s of 1/0.9 and 1/0.6 are shown in Figures 4.14 and 4.15, respectively. However, this combination was chosen mainly to produce grout for PAC production, it is advantageous to study the rheology of different grouts using different w/c and c/s ratios. There is quiet better data distribution in this case where *g* appears to decrease exponentially with the increase in w/c ratio especially at c/s of 1/0.9. Many grouts of zero *g* values were recorded especially at c/s of 1/0.6.

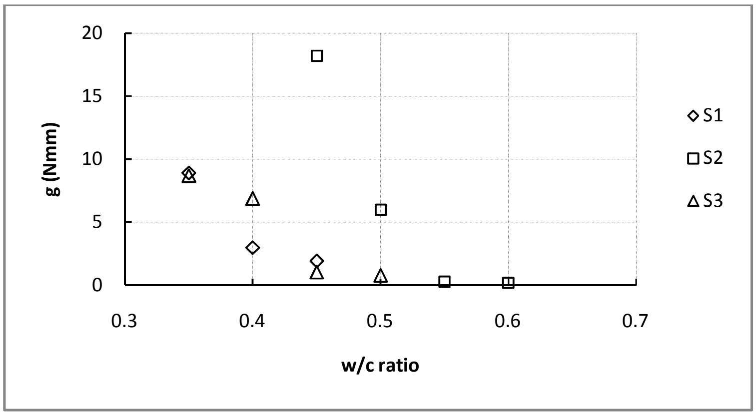


Figure 4.14 Yield stress vs w/c ratio at c/s of 1/0.9 with 1% SP and 20% Pfa

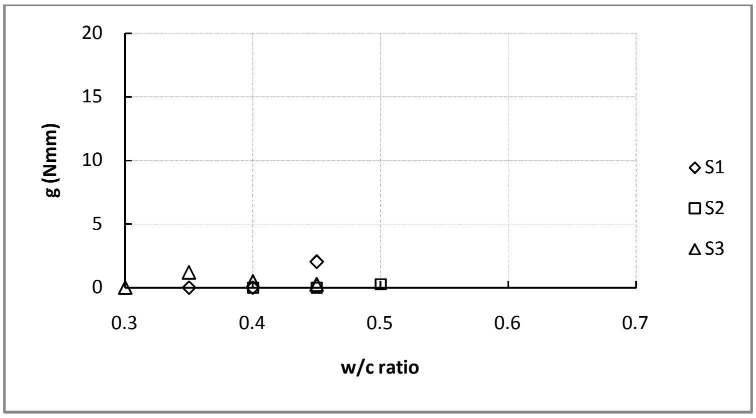


Figure 4.15 Yield stress vs w/c ratio at c/s of 1/0.6 with 1% SP and 20 % Pfa

Table 4.4 Rheology test results for grouts of 1% SP and 20% Pfa

Mix No.	**Sand type**	**c/s ratio**	**w/c ratio**	***g* (Nmm)**	***h* (Nmms)**	**Flow time**	**Bleeding (%)**	**Flow speed**
1	S1	1/0.9	0.50	0	2	29	2.50	12.11
2	S1	1/0.9	0.45	1.93	4.00	69	1.20	9.34
3	S1	1/0.9	0.40	3.00	5.30	N/A	0.20	3.33
4	S1	1/0.9	0.35	8.90	15.69	N/A	0	2.10
5	S1	1/0.6	0.45	2.03	1.15	30.25	1.90	28.57
6	S1	1/0.6	0.40	0	3.70	57	0.20	20.74
7	S1	1/0.6	0.35	0	9.63	127	0	6.00
8	S1	1/0.6	0.30	0	20.35	N/A	0	3.48
9	S2	1/0.9	0.60	0.20	0.66	23	5.00	32.68
10	S2	1/0.9	0.55	0.27	2.65	35	1.90	17.92
11	S2	1/0.9	0.50	6.01	3.65	92	1.20	11.60
12	S2	1/0.9	0.45	18.22	10.50	N/A	0	3.11
13	S2	1/0.6	0.50	0.26	1.23	24	2.50	30.12
14	S2	1/0.6	0.45	0	2.31	37	1.90	18.18
15	S2	1/0.6	0.40	0	5.57	N/A	0.60	9.52
16	S2	1/0.6	0.35	9.30	8.98	N/A	0	3.17
17	S3	1/0.9	0.50	0.79	1.52	27	2.50	28.10
18	S3	1/0.9	0.45	1.05	3.4	57	1.20	12.82
19	S3	1/0.9	0.40	6.88	6.46	N/A	0.50	4.53
20	S3	1/0.9	0.35	8.70	17.50	N/A	0	1.04
21	S3	1/0.6	0.45	0.23	1.16	26	1.50	31.45
22	S3	1/0.6	0.40	0.49	1.79	35	0.60	25.91
23	S3	1/0.6	0.35	1.20	6.08	85	0.40	7.51
24	S3	1/0.6	0.30	0	14.70	N/A	0	2.42

Figures 4.16 and 4.17 exhibit the effect of w/c ratio on the plastic viscosity of grouts at c/s of 1/0.9 and 1/0.6, respectively. Both cases of c/s ratios show that *h* of grouts decrease with the increase in w/c ratio. S2 shows higher values of *h* than others especially at high sand content due to its high surface area and high roughness which increases the number of contact points of particles; those contact points increase the friction between sand particles which increases the grout viscosity. Grouts of c/s ratios of 1/0.6 show closer values of *h* using different sands because of the less sand quantity. The higher quantity of sand at c/s of 1/0.9 in grouts resulted in higher *h* compared with c/s ratio 1/0.6 grouts as presented in Table 4.4.

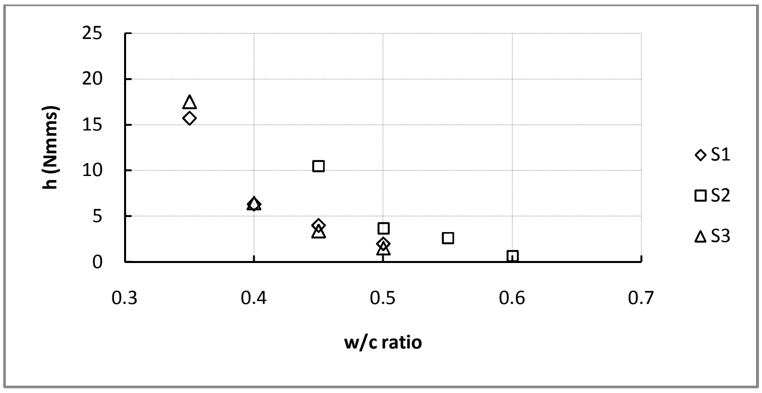


Figure 4.16 Grout plastic viscosity vs w/c ratio at c/s of 1/0.9 with 1% SP and 20 % Pfa

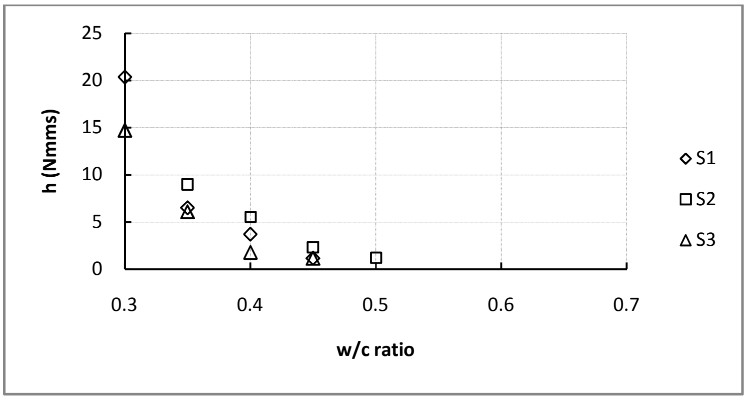


Figure 4.17 Grout plastic viscosity vs w/c ratio at c/s of 1/0.6 with 1% SP and 20 % Pfa

4.6 Conclusions

Grout was produced at different sands, w/c and c/s ratios, and different SP and Pfa dosages, and then its fresh properties were measured by different devices. The effect of w/c and c/s ratios on the rheological properties of grouts by employing SP and Pfa were investigated. From the presented study, the following conclusions can be drawn

- Cement paste rheology has been affected by addition of superplasticizer admixtures to the mix, addition of 1% and 2% of SP results in lower viscosity than non SP pastes. Zero yield stress values were also recorded because of the affect of SP.
- The effect of sand size and grading on grout plastic viscosity are not important at high SP content, where addition of SP at 2% resulted in closer plastic viscosity values for grouts of different sands at the same w/c and c/s ratios.
- Grout rheological properties decrease with the increase in water content for all grouts using SP and Pfa at different c/s ratios. High SP content of 2% at medium

and high water contents resulted in grout segregation, the sand was precipitated in the mixer bowel immediately after the mixer stopped.

- C/s ratio of 1/0.6 at high SP content resulted in many grouts of zero yield stress because of no internal friction at low sand content. S2 resulted in the highest yield stress values than others where S1 and S3 show close results. The use of single size sand S4 was abandoned from the lab work because of the high segregation resulted when SP was used.
- Grouts of 20% Pfa of the cement replacement and 1% SP show better relations between yield stress and w/c ratio than grouts of 1% SP only due to less segregation and very low bleed. As a result it is beneficial employing Pfa as a replacement additive at 20% of the cement weight with 1% SP in grout for the production of PAC.

CHAPTER 5: EFFECT OF FRESH GROUT RHEOLOGY ON THE INJECTION PROCESS FOR THE PRODUCTION OF PAC

5.1 Introduction

Preplaced aggregate concrete (PAC) is produced by placing the coarse aggregate into the forms and grouting the aggregate voids by high workability cement based grout. Consequently, it is the grout flow ability which underpins the quality of PAC. This chapter investigates the ability of different grouts to penetrate through the coarse aggregate with and without superplasticiser and pulverized fuel ash in the mix. Moreover, a suitable combination of superplasticizer and fly ash in grout injection will be investigated.

As grout rheological properties using different sand types and contents at different water contents were investigated with and without chemical and mineral admixtures in chapter four, grout mixes presented in Tables 4.1, 4.2, 4.3 and 4.4 will be used to define the required workability for PAC production.

The whole picture of concrete production can be clarified by investigating the effect of fresh grout properties on the injection process through the coarse aggregate. Rheology of different grouts which are capable of penetrating through coarse aggregate under gravity action at 2m head will be identified experimentally in this chapter. The purpose of this work is to identify the rheology of grouts which can penetrate the stone skeleton and produce satisfactory PAC. Rheology of grouts presented in chapter 4 will be used in this chapter to investigate their effect on the injection threshold through a coarse aggregate mass. In addition, the relations between grout density and grout rheological properties and grout/concrete (G/C) ratio by weight will be investigated.

5.2 Coarse aggregate

It is very important to study the coarse aggregate because it is the skeleton of the resulting concrete. As coarse aggregate particles are in contact before and after grout injection, its selection is of great importance (Abdelgader, 1995). Crushed stone or natural gravel can be used (ACI 304.1R, 1997). On the other hand, flaky and elongated stones are not preferred because they may create narrow channels which may affect the flow of grout (Littlejohn, 1984). Angular and irregular basalt was used by Awal (1985) as a coarse aggregate in the production of PAC with maximum size of 38mm to produce cylindrical concrete specimens of 150mm diameter and 300mm height. Moreover, rounded and irregular aggregate with maximum aggregate size of 80mm were used in the production of 300mm PAC cubic samples by Abdelgader (1996 and 1999).

For PAC, a minimum void ratio of coarse aggregate is preferred after compaction to minimize the quantity of grout because of economy and to minimize the temperature rise in massive construction. The control of void ratio can be attained by using graded aggregate. It is recommended that the maximum size of coarse aggregate should not exceed the third of the minimum dimension of the form to be concreted (ACI 304.1R, 1997). On the other hand, the smallest particle size of coarse aggregate is controlled by the maximum particle size of sand used in the grout because the minimum coarse aggregate particle determines the channels through which the grout will pass. For ease of grout penetration through the voids of the coarse aggregate, the maximum size of sand is less than one-eight or one-tenth of the minimum size of coarse aggregate for a natural rounded sand and crushed angular sand, respectively, and for both cases the oversize is less than 5% (Littlejohn, 1984).Void content usually ranges between 35 to 50 % depending on the gradation of coarse aggregate (ACI 304.1R, 1997).

In the present study, natural gravel of maximum aggregate size of 38 mm was used as a coarse aggregate. It is available in the UK, commercially known as Scottish pebbles. It is hard, clean from any impurities with water absorption of 0.017. Coarse aggregate gradation is in the range suggested by ACI 304.1R (1997) as shown in Figure 5.1. The maximum aggregate size of 38.1mm was chosen to cast concrete of 150mm cubes which is less than the third of the form as suggested by ACI 304.1R (1997).

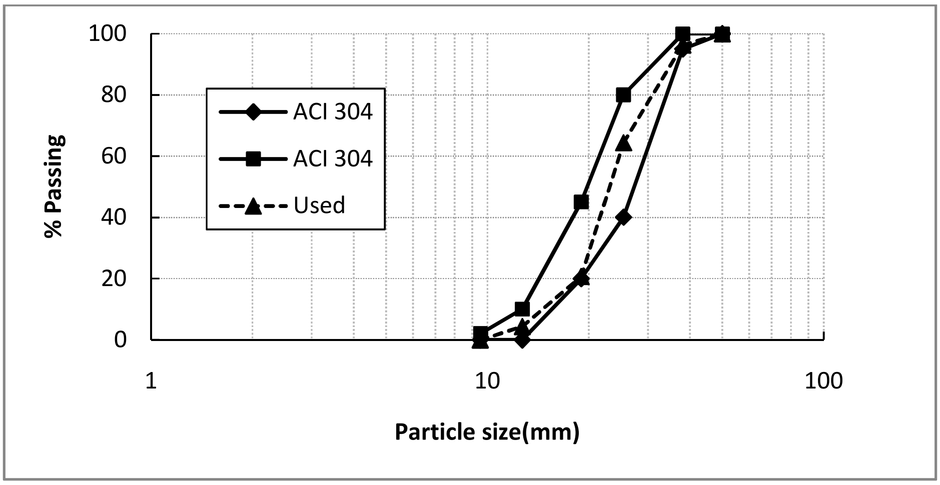


Figure 5.1 Coarse aggregate gradation with ACI 304.1 R, 1997 limitations

5.3 Grouts used

Grouts presented in section 4.5 were used in the injection process through the coarse aggregate in order to produce PAC. First, grouts without any mineral and chemical admixtures were produced at different w/c ratios and c/s of 1/0.9 and 1/0.6 using sands

S1, S2, S3 and S4. After that, SP was added at 1% and 2% to the grouts and the effect on the injection threshold was investigated. Finally, SP of 1% was employed and 20% of the cement was replaced by Pfa; the resulting grout penetration through the coarse aggregate was investigated. S4 was removed from the lab work when SP employed because of the high segregation resulted as presented in section 4.5.2.

5.4 Testing procedure

Coarse aggregate used was soaked in water for 24 hours to get fully saturated aggregate. Then, aggregate was washed with water to remove any dust and impurities which may decrease the injection rate or bond between aggregate and grout. After that, a solid plastic pipe of 20 mm diameter and 2 m height was inserted into the middle of 150 mm cubic mould. Following that, coarse aggregate was wiped with a cloth and weighed and put into the mould around the pipe. Fresh grout was poured through the funnel fixed at the upper end of the pipe and injected under gravity action into the stone skeleton (Abdelgader 1995; Ganaw, 2002; and Nowek et al., 2007). The pipe was withdrawn after grout flow stopped and the injection process was achieved by grout covering all the coarse aggregate. Finally, the surface was finished and the concrete was left in moulds for 24 hours and weighed.

The amount of grout penetration among the coarse aggregate voids changes according to its consistency or rheology. High flow grouts penetrated easily through the coarse aggregate. On the other hand, very low flow grouts did not even penetrate through the funnel and the pipe. Medium consistency grouts varied in the penetration where some grouts did not penetrate through the whole coarse aggregate mass. Because the quantity of grout injected depends on the degree of consistency, then it is of interest investigating its effect on the production of PAC.

As the quantity of coarse aggregate in the mould was known, it was possible to calculate the quantity of grout injected after 24 hours of casting from the difference in weight between PAC and coarse aggregate. Grout injection expressed as a weight ratio between the injected grout to the concrete produced (G/C).

5.5 Effect of grout rheology on the injection process

5.5.1 Effect of yield stress parameter on the injection process

The relation between G/C ratio and *g* for all grouts presented in chapter 4 are presented in Figure 5.2. The relation between G/C ratio and *g* shows that a threshold in the range of about (6-7) Nmm in the injection process exists. Moreover, grouts of *g* values more than 7 Nmm are no longer injected through the whole mass of coarse aggregate. It is of interest to observe that grout yield stress parameter (*g*) gave the same threshold despite the difference of materials used. As a result, yield stress property can be relied on in the grout injection process in the production of PAC. Similarly, Yahia A. et al (2001) reported that, the existence of yield stress can significantly influence the flow rate and capacity of filling of non-Newtonian cement based grouts especially for mixtures placed without vibration. They added, the yield stress can be used as an index of quality control of self leveling systems.

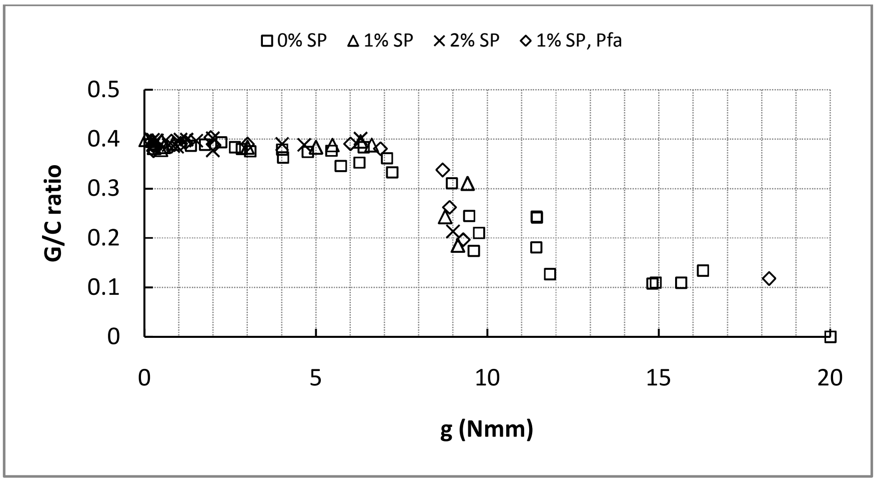


Figure 5.2 G/C ratio vs yield stress for all grouts

5.5.2 Effect of grout plastic viscosity parameter on the injection process

For comparison between the effects of using different materials added, the relations between G/C ratio and *h* for all mixes are presented in Figure 5.3. Mixes without any chemical and mineral admixtures show different injection threshold at around 2 Nmms where other mixes exhibit higher injection threshold at around 5 to 6 Nmms for SP grouts only and 6.5 Nmms where Pfa employed at 20% with 1% SP.

The high *h* threshold value at which full injection occurred in the presence of SP can be attributed to the ability of grouts to fill up the aggregate voids because of the higher grout cohesion. In other words, the self leveling behavior of grout at higher viscosity has the ability to fill the voids. Grouts contain Pfa show slightly higher threshold than others due to the higher cohesion resulted. The higher cohesion is attributed to the addition of Pfa in the presence of SP as reported by Jefferis and Sarandilly (1988) which can be certified also to the ability of getting required flow at low water content. It can be concluded that *h* threshold required for full injection differs according to whether chemical and mineral admixtures employed in the mix or not. This result is different from the yield stress where all mixes gave the same *g* threshold in spite of the difference in material added as presented in the previous section. It is suggested that the plastic viscosity is not as important parameter as the yield stress parameter in controlling the penetration of grouts.

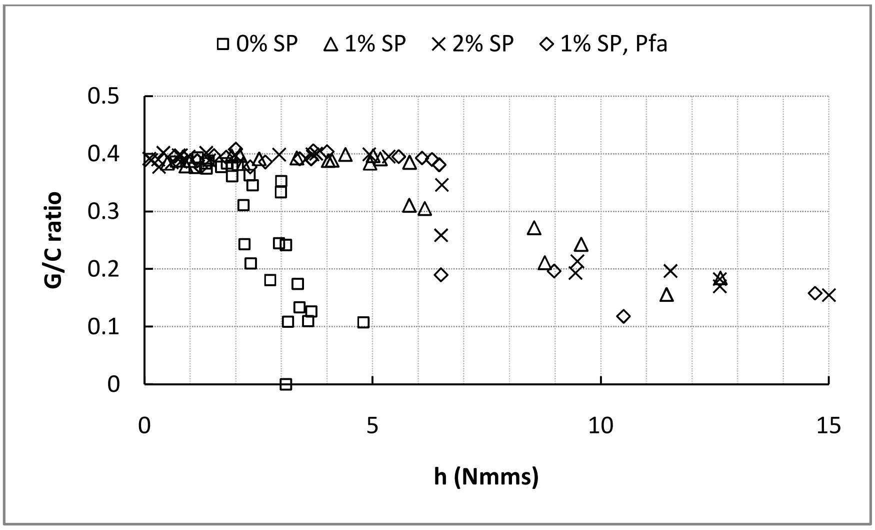


Figure 5.3 G/C ratio vs plastic viscosity for all mixes

5.5.3 Effect of grout flow time on the injection process

Relation between G/C ratio and flow time for all grout is illustrated in Figure 5.4. Full injection threshold changes slightly with the change in grout material added. The lowest value of the flow time threshold occurred by grouts without SP at around 65 seconds. On the other hand, the highest threshold of around 90 seconds is resulted from 1% SP and 20% Pfa grouts, and grouts of only SP show injection threshold at around 75 seconds. Although ACI 304.1R (1997) and Swaddiwudhipong (2002) suggested that the flow time for PAC is lower than 35 seconds, the results from this investigation show that, it is possible to inject grouts for PAC with flow time up to 90 seconds depending upon the admixture used in the mix. This difference is attributed to the efflux of grout flow through the flow cone orifice, as the specification suggested ending the measuring time at the moment when the grout efflux starts once a gap can be noticed in the funnel orific. The behavior of self leveling grouts makes the moment of efflux cut is not sudden to stop the measuring time concluding that the sensitivity of the flow cone test is not accurate especially for low consistency grouts.

It can be summarized that, the effect of flow time of grout injection changes according to the material added. Consequently, identifying the grout workability by the flow time test only is not enough for PAC production.

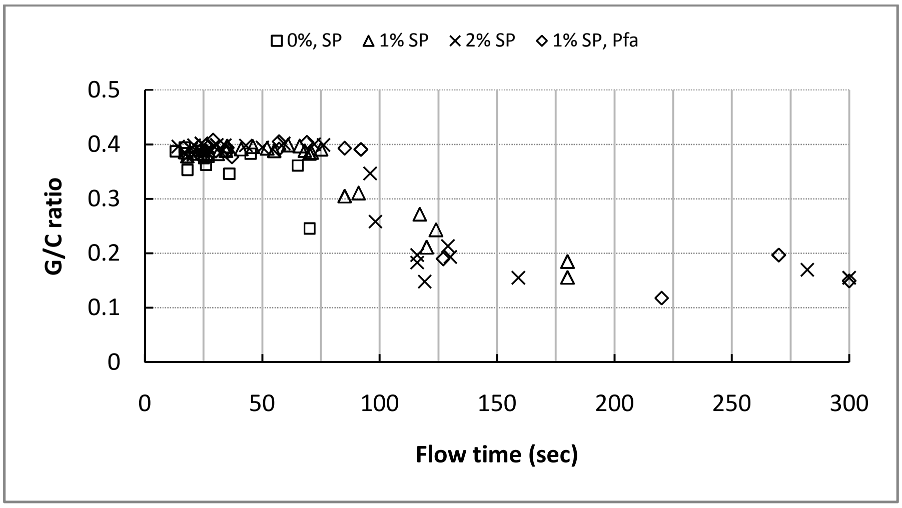


Figure 5.4 G/C vs flow time for all grouts

5.5.4 Effect of grout speed on the injection process

Grout speed was measured by the flow meter as presented in section 4.3.1 and the test results were presented in Tables 4.1to 4.4 . The effect of grout speed on G/C ratio is shown in Figure 5.5. As the speed of grout increases the injection percentage increases to reach a certain threshold after which all grouts achieved full injection. The lowest threshold was achieved by grouts of 1% and Pfa where the highest one was achieved by grouts of 2% SP. Concluding that, grout speed threshold differs according to the material type and dosage employed in the mix. This difference has come from the variation in the test sensitivity in measuring grout speed which could be attributed to effect of grout unit weight as shown by grouts of Pfa. As a result, grout injection threshold using different mixes cannot be defined only by grout speed test.

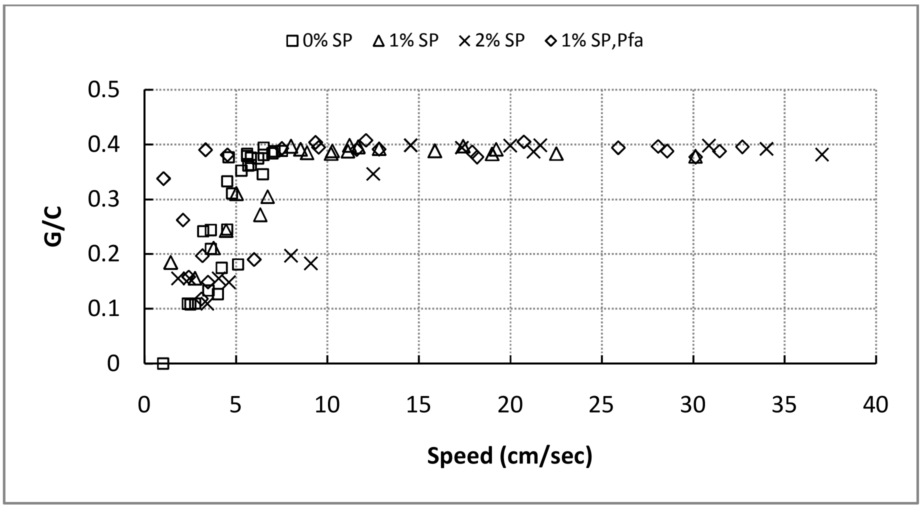


Figure 5.5 G/C vs speed for all grouts

5.6 Relation between G/C ratio and water bleeding in grout

Water bleeding in grout is an important factor because of its effect on the resulting concrete properties. Excess water in grout traps underneath the coarse aggregate and weakens the bond in the transition zone between the hardened grout and coarse aggregate and that of course adversly affects on concrete properties (Mehta, 1986). In this study, grout bleeding percentage was measured as described in section 4.3.2 and bleeding results were presented in Tables 4.1 to 4.4. The relation between grout water bleed and G/C ratio is investigated for all mixes below. Bearing in mind that, the bleeding measurments were taken after 3 houres from mixing and the injection was done immediately after mixing, however the relations show that it is possible to produce PAC with grouts of less than 5% bleeding as presented in Figure 5.6. Grouts of only 1% SP and grouts of 1% SP with 20% Pfa present full injection at very low bleeding ratios of less than 1%. Consequently, good quality PAC can be produced by injecting grouts of 1% SP and 20% Pfa. On the other hand, grouts of 2% SP were fully injected with 0.4 G/C ratio at high water bleeding and that will affect adversley on the produced concrete properties. The excess water will trap between the grout and coarse aggregate and weakens the resulted concrete. It can be concluded that, bleeding of grout can be used as an indication for the quality of PAC production.

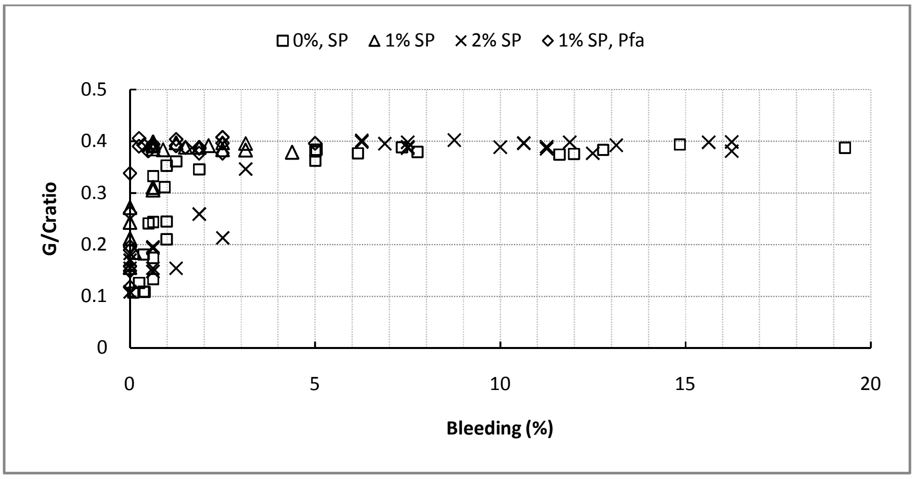


Figure 5.6 G/C ratio vs water bleeding percentage for all mixes

5.7 Effect of grout density on the production of PAC

Although the grout head was kept constant at 2m for all mixes, the injection pressure was not the same because of the change in grout unit weight. Grout unit weight changes according to different factors like w/c ratio, c/s ratio and the additives and admixtures used and their percentages in the mix. Consequently, it is worth studying the change in grout density on its injection through the coarse aggregate, and that is to define the unit weight of different grouts at which full injection occurs.

The effect of grout density on the injection threshold percentage is shown in Figure 5.7. Grout threshold differs according to the material added to the mix and its percentage. After a threshold grouts illustrate a decrease in injection percentage as the density increases and this adverse result is attributed to the decrease in grout fluidity at high density. In other words, grouts with high density are accompanied with higher yield stress which minimizes the injection rate. For the same grout SP percentage, the difference in injection ratio has come from the effect of other factors such as w/c ratio and sand type and content. Grout unit weight to define the threshold of different grouts in the injection process alone is not enough where grout rheological properties have to be taken into account.

The effect of grout unit weight on the injection process at constant rheological properties is recommended for further investigation. In addition, the effect of high pressure by the help of pumps on grout injection is also suggested to be investigated using grouts of different rheological properties. Consequently, the relation between pressure and rheological properties of grout and G/C ratio can be clarified for large scale concreting of PAC.

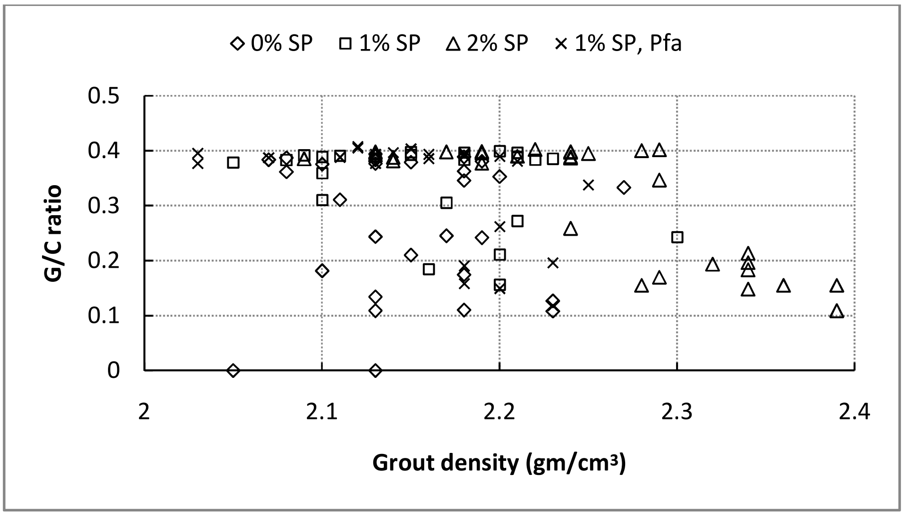


Figure 5.7 G/C ratio vs density for all grouts

5.8 Importance of yield stress of grout for PAC production

It has been shown that the yield stress of grout is the most important and appropriate property to define the threshold of grout injection. It gave the same threshold for all grouts regardless of all other factors such as material type or quantity used in the mix. Grout of yield stress of 7 Nmm and less was found to be inject-able among the voids of rounded coarse aggregate mass under gravity action at 2m head to cast 150 mm PAC cubes. It is of interest to the grout specifier or designer to know how to produce grout of yield stress of 7 Nmm or less from the grout mix proportion. As presented in section 3.7.2, Equation 3.7, grout yield stress is a function of cement paste yield stress and excess paste thickness. Consequently, by knowing paste yield stress and excess paste thickness from different factors like, w/c ratio, c/s ratio, sand void ratio and sand surface area, then it is possible to design the required grout yield stress which of course less than 7 Nmm.

5.9 Conclusions

In this chapter, fresh grout injection through coarse aggregate in the production of PAC was investigated using different sands. Different water and sand contents in the mix were used with and without chemical and mineral admixtures. The unit weight and degree of grout consistency required for the injection were investigated by measuring grout density and grout rheological properties like, yield stress, plastic viscosity, flow time, grout speed and water bleed. From the presented results, the following conclusions can be shown:

- Grout yield stress results show a threshold in the range of about (6-7) Nmm in the injection process through the coarse aggregate for all mixes. Moreover, the same threshold was recorded despite the difference in ingredients and materials added. As a result, yield stress property can be considered as an indication of grout injection in the design of PAC.
- Grout design for PAC can be achieved from knowing paste yield stress parameter and excess paste thickness from different factors such as, w/c ratio, c/s ratio, sand voidage and sand surface area as presented in Equation 3.7. Then it is possible to design the required grout yield stress of less than 7 Nmm.
- Plastic viscosity test results show an injection threshold differs according to the material added to the mix. For instance, plastic viscosity threshold of about 2 Nmms for non added admixture grouts, 5 to 6 Nmms for grouts with SP only and 6.5 Nmms where 20% Pfa employed with 1% SP. These results show that grout injection ability changes according to the material added to the mix from the plastic viscosity point of view.

- Identifying grout injection threshold by the flow time test showing that; the lower value of the flow time threshold occurred by grouts of no added admixtures with time less than 65 seconds. Then, grouts of only SP with flow time up to 75 and finally grouts of 1% SP and 20% Pfa with higher flow time at up to 90 seconds were injected through the coarse aggregate successfully.
- Grouts of 1% SP and 20% Pfa were fully injected at very low bleeding rates, following that grouts contain only 1% SP and finally grouts of 2% SP injected at high bleed rates. Concluding that, PAC is better produced by injecting grouts of 1% SP and 20% Pfa because of very low water bleeding and consequently ensuring lower volume of voids between grout and coarse aggregate.
- Effect of grout density on the grout-concrete injection ratio shows different injection thresholds according to the material added to the mix and its percentage. After certain injection threshold of each grout, G/C decreases as the density increases concluding that grout rheology is the responsible in decreasing the injection rate at high density not only the density. Consequently, the effect of grout unit weight on the injection process at constant rheological properties is recommended for further investigation. Moreover, the effect of pumping grouts at high pressure rates on the injection is also suggested to be investigated using grouts of different rheological properties. After that, the relation between pressures, rheological properties of grout and G/C ratio can be clarified for large scale concreting of PAC.

CHAPTER 6: EFFECT OF GROUT RHEOLOGY ON ITS HARDENED PROPERTIES AND CORRELATION BETWEEN GROUT PROPERTIES

6.1 Introduction

In addition to the coarse aggregate role in manufacturing of PAC, grout is a main component and its properties are very important as they underpin the quality of produced concrete. As the effects of w/c ratio and c/s ratios on a wide range of grout rheological properties were investigated in chapter 4 and the rheology injection threshold was defined in chapter 5. This is the third and last stage of the lab work as shown in Appendix B, where 18 selected grouts of high workability and low bleeding will be used to manufacture hardened grout and PAC, and their properties will be investigated in chapters 6 and 7.

The mechanical properties of hardened grouts will be studied as they give an overall picture on the quality of hardened grout and that is important because of their direct impact on the PAC properties. In addition, grout sorption of water will be investigated because of the importance of grout sorptivity on the durability of produced PAC. Low permeability of grout is also useful in applications such as duct grouting and ground anchorage where corrosion protection is necessary (Crosseley, 1991).

This chapter mainly divided into three parts; the first part gives a further investigation on the rheology of fresh grouts where the second part presents the relations between fresh and hardened grout properties; in these relations w/c ratio, sand type and content in grout were considered in the analysis. The third part shows the correlation between grout hardened properties like flexure, compressive strengths and sorptivity and this correlation will enable to approximate prediction between two parameters of hardened grout properties like, flexure strength and compressive strength or compressive strength and sorptivity. An investigation on the correlation between hardened grout and PAC properties will be discussed in chapter 7.

Eighteen grout mixes were chosen from the work presented in chapter 5 after defining the required workability to produce PAC. All grouts were able to penetrate the coarse aggregate and filled the coarse aggregate mass of 150mm cubes. 1% SP with 20% Pfa was employed at three different w/c ratios and at c/s ratios of 1/0.9 and 1/0.6 for sands S1, S2 and S3.

6.2 Fresh Grout

Eighteen grout mixes presented in Table 6.1of high flow-ability to produce grout and PAC were prepared. Grouts were mixed by Hobart mixer according to the procedure presented in section 3.4.2. Grout rheological properties, flow time, flow speed and bleeding tests were measured.The effect of w/c, c/s, sand type and sand content on grout rheology is investigated. Moreover, relations between grout flow time, speed and plastic viscosity are also studied in this section. Relations between fresh grout yield stress and other grout properties are not included because many grouts have resulted in zero *g* values as shown in Table 6.1.

Table 6.1 Grout rheology and bleeding test results

Mix No.	**Sand type**	**c/s ratio**	**w/c ratio**	***g*** **(Nmm)**	***h*** **(Nmms)**	**Flow time**	**Bleeding (%)**	**Flow speed**
1	S1	1/0.9	0.50	0	2.00	43	2.50	20.16
2	S1	1/0.9	0.45	0.56	4.04	77	1.20	10.22
3	S1	1/0.9	0.40	1.27	9.88	130	0.60	5.03
4	S1	1/0.6	0.45	3.61	1.00	33	3.10	24.15
5	S1	1/0.6	0.40	0	2.63	66	1.20	15.06
6	S1	1/0.6	0.35	0	8.85	137	0	7.29
7	S2	1/0.9	0.60	0.7	0.39	23	2.50	34.72
8	S2	1/0.9	0.55	0.62	1.20	38	1.90	22.12
9	S2	1/0.9	0.50	4.85	2.89	86	1.50	11.04
10	S2	1/0.6	0.50	0	0.72	25	1.60	28.09
11	S2	1/0.6	0.45	0	1.98	46	1.00	18.65
12	S2	1/0.6	0.40	0.59	5.12	97	0.40	11.13
13	S3	1/0.9	0.50	0.63	1.14	31	1.90	22.73
14	S3	1/0.9	0.45	1.88	2.50	50	1.00	13.44
15	S3	1/0.9	0.40	4.64	4.37	121	0.60	5.71
16	S3	1/0.6	0.45	0	1.05	26	2.50	28.09
17	S3	1/0.6	0.40	0	2.63	49	0.60	17.60
18	S3	1/0.6	0.35	0.74	6.38	134	0	9.14

6.2.1 Effect of water content on the flow time of grout

Figure 6.1 shows the effect of w/c ratio on the flow time of grouts at c/s of 1/0.9 and 1/0.6. All relations show that flow time decreases with the increase in w/c ratio; the same relationship was presented by Awal (1984) and Huang (2001). At the same w/c ratio, grouts of S2 show the highest values of flow time than others where S3 grouts are the lowest at the same c/s ratio. Moreover, grouts of c/s of 1/0.9 show higher flow time than those of c/s of 1/0.6 for the same sand type at the same water content. Consequently, higher flow was produced by grouts of low sand content at c/s of 1/0.6.

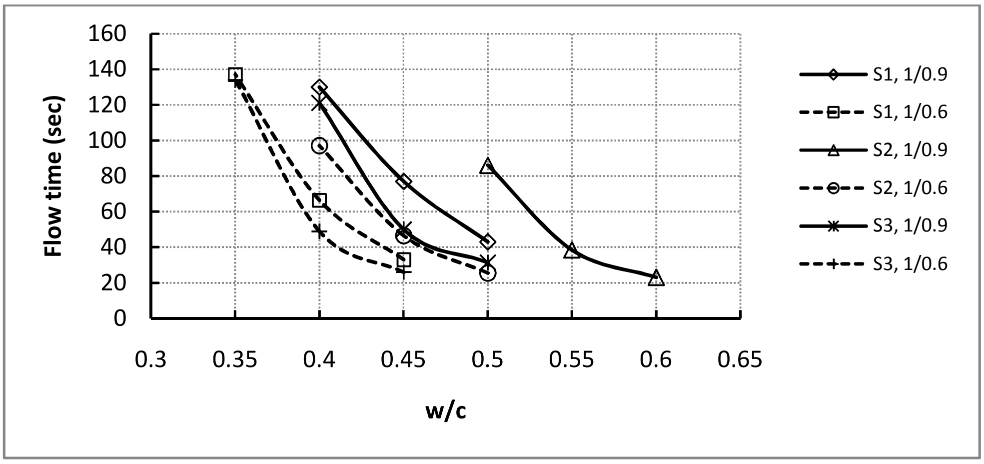


Figure 6.1 Grout flow time vs w/c ratio at different c/s ratios

6.2.2 Effect of water content on the plastic viscosity of grout

Figure 6.2 shows the relation between plastic viscosity parameter (*h)* of grout and w/c ratio at c/s of 1/0.9 and 1/0.6. In both cases of c/s ratios, *h* decreases with the increase in water content in grout due to the effect of cement paste in grout, and this is a reflection of paste effect as shown in Figure 4.1. S2 grouts show the highest *h* values than others, on the other hand S3 grouts show the lowest values. Moreover, grouts of high sand content of c/s of 1/0.9 show higher *h* than those of c/s of 1/0.6. In addition, at c/s of 1/0.6, S1 and S3 have very close *h* values at all w/c ratios concluding that sand has a minor effect on grout viscosity at lower contents.

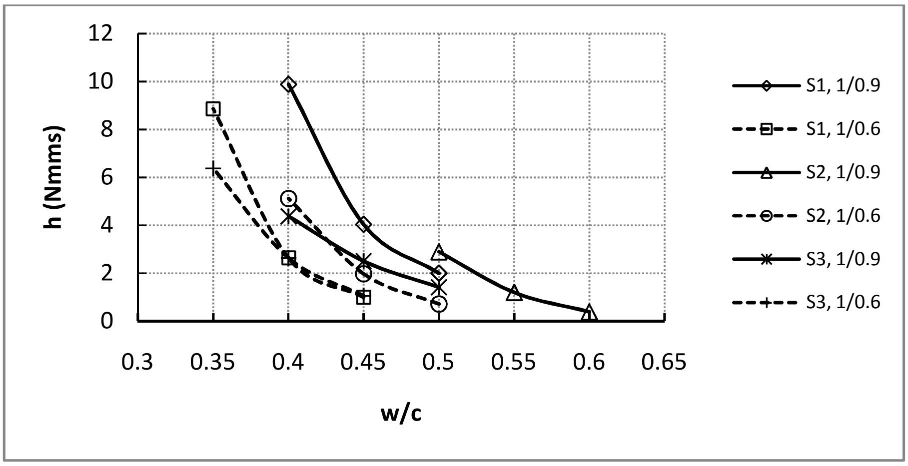


Figure 6.2 Grout plastic viscosity vs w/c ratio at different c/s ratios

6.2.3 Effect of water content on the grout speed

Figure 6.3 illustrates the relation between grout speed and w/c ratio at c/s ratios of 1/0.9 and 1/0.6. Grout speed increases with the increase in w/c ratio for both cases of c/s ratios; this increase was expected because grout flow increases with the increase in w/c ratio. S3 grouts show the highest speed of all grouts and the lowest speed was shown by S2 grouts at the same c/s and w/c ratios. Grouts of high sand content of c/s of 1/0.9 show lower speed than those of c/s of 1/0.6. The lower speed of high sand content grouts can be attributed to the high internal forces which minimizes the grout speed. In both cases of sand contents at the same water content, S1and S3 grouts show higher speed than S2 grouts. This is attributed to the high volume of voids of S2 which consumes more paste than others and that minimizes the grout workability. The same conclusion was reported by Cortes, et al., (2008).

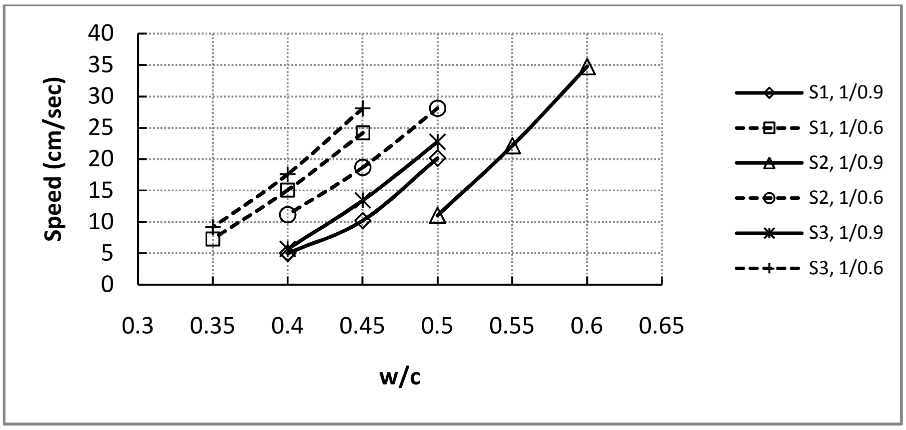


Figure 6.3 Grout speed vs w/c ratio at different c/s ratios

6.2.4 Effect of water content on grout bleeding

Figure 6.4 shows the relation between grout water bleeding and w/c ratio at c/s of 1/0.9 and 1/0.6. Bleeding rate in grout increases with the increase in w/c ratio using different sands and contents. At the same w/c and c/s ratios S1 grouts show the highest bleeding and S2 grouts show the lowest bleeding rates in both cases of c/s ratios. Comparison between grouts of c/s of 1/0.9 and 1/0.6 shows that bleeding rate decreases with an increase in sand content at the same w/c ratio and the same sand type. It is shown also that all grouts presented low bleeding percentages of less than 3.5 %. This low bleeding rate is necessary to ensure good bond between hardened grout and coarse aggregate in the production of PAC. In addition, the excess water in grout will trap in the transition zone between hardened grout and coarse aggregate and that will affect adversely on the properties of resulting concrete, (Awal, 1985; Mehta, 1986; and Larrard, 1999).

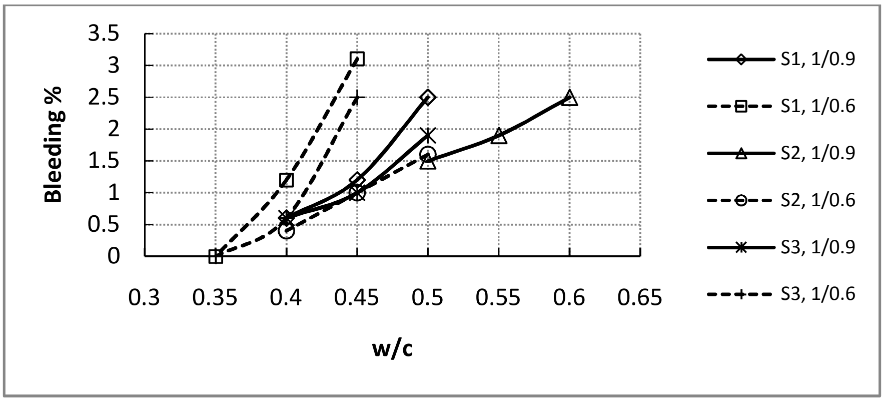


Figure 6.4 Grout bleeding vs w/c ratio at different c/s ratios

6.2.5 Relations between flow time of grout and plastic viscosity

The relation between flow time and plastic viscosity of grout at c/s of 1/0.9 and 1/0.6 are shown in Figures 6.5 and 6.6, respectively. Grout flow time increases with the increase in *h* value for both cases of c/s ratio. In other words, grouts of high plastic viscosity need more time to empty the flow funnel than those of lower viscosity grouts. Figure 6.6 shows that, there is a good correlation between flow time and *h* at c/s of 1/0.6 despite the difference in sand type because the flow is controlled by the cement paste at low sand content. Some scatter data were noticed for high sand content grouts at c/s of 1/0.9 especially at high viscosity values. This scatter is related to the flow time test measurments for low fluidity grouts, it is difficult to decide the ending time of grout flow through the funnel nozzle because the flow cut is not sudden.

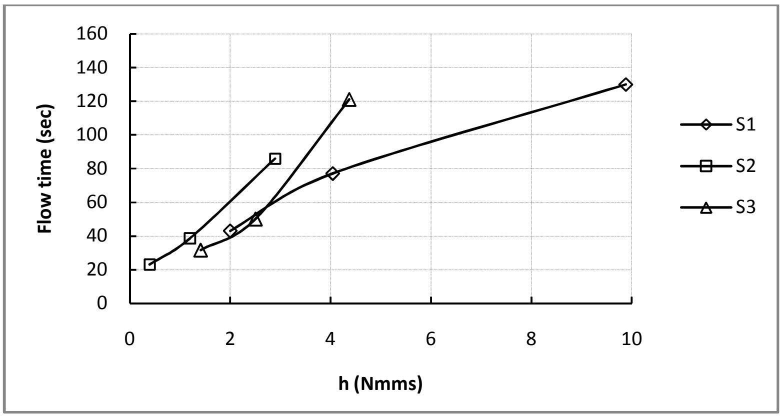


Figure 6.5 Grout plastic viscosity vs flow time at c/s of 1/0.9

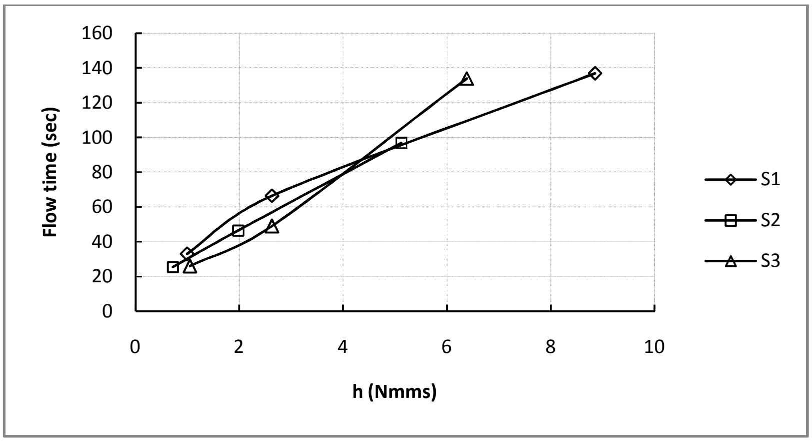


Figure 6.6 Grout plastic viscosity vs flow time at c/s of 1/0.6

Due to the correlation between grout flow time and *h* presented bove, it was worth trying to get a general relation regardless of sand type and content. As presented in Figure 6.7, a linear relation was found between flow time and *h* with correlation factor of 93.6 %. This relation can be used in calculating grout plastic viscosity from its flow time up to flow factor around 130 sec.

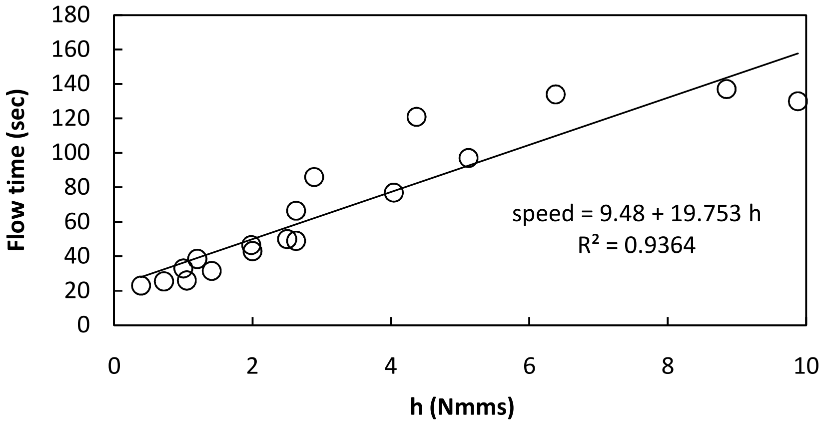


Figure 6.7 Flow time vs plastic viscosity for all grouts

6.2.6 Relations between grout speed and plastic viscosity

The relation between grout speed in the flow channel and plastic viscosity at c/s of 1/0.9 and 1/0.6 are shown in Figures 6.8 and 6.9, respectively. Grout speed decreases with the increase in *h* value in both cases of c/s ratios. Although the sand type and content were different, a good correlation was observed between the grout speed and *h*. This good correlation could be attributed to the flow channel itself, because the grout was released to move freely in a wide space better than the flow funnel test.

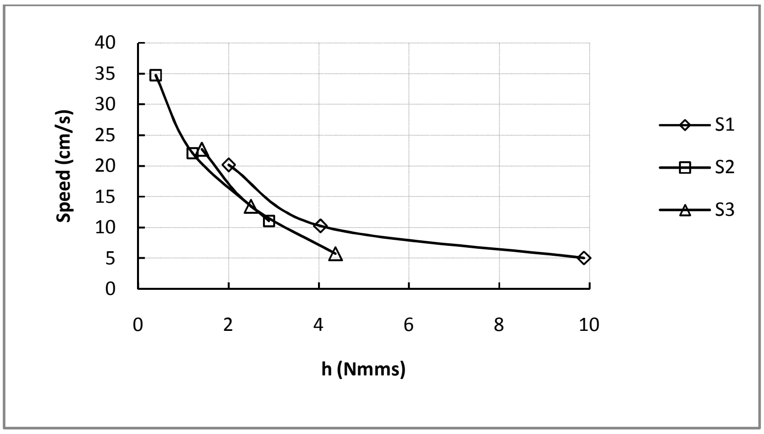


Figure 6.8 Speed vs plastic viscosity of grout at c/s of 1/0.9

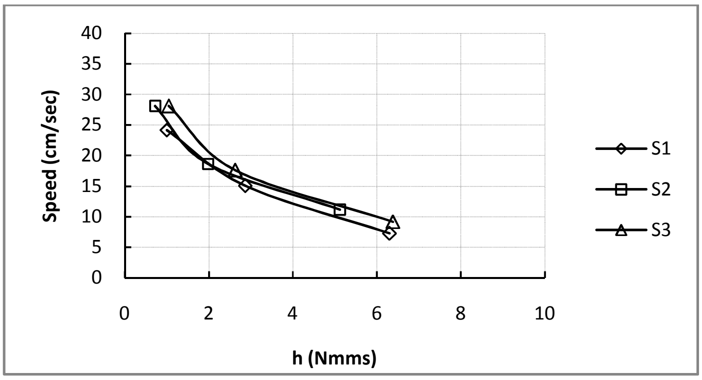


Figure 6.9 Speed vs plastic viscosity of grout at c/s of 1/0.6

The presented relations in Figures 6.8 and 6.9 suggest there might be a general relation between grout speed and viscosity despite the change in sand type or content. Figure 6.10 shows that, a good correlation exists between grout speed and *h* with correlation coefficient of 0.934. This relation is useful in calculating grout speed from its plastic viscosity parameter up to 10 Nmms.

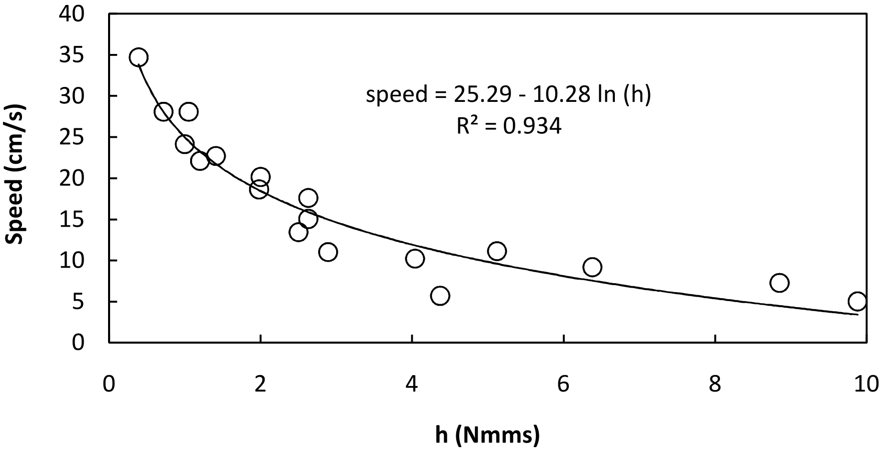


Figure 6.10 Grout speed vs plastic viscosity for all grouts

From the above relations between grout plastic viscosity, flow time and grout speed, it was shown that grout speed has a good correlation with *h* up to 10 Nmms and the flow factor good correlates with *h* up to around 6 Nmms. Then it is suggested that fluidity of high and medium grouts can be measured by the modified flow meter as well as by the flow funnel as a complementary to the rheology tests. Although the correlation factor is the same around 93% in the two tests with *h*, modified flow channel test seems to be a better sensitive in measuring the grout consistency than the flow funnel especially at high *h* values. Moreover, these tests are very useful where the rheology testing devices are not applicable especially in the field work. The presented correlation equations between grout plastic viscosity parameter, flow time and grout speed are also useful in the prediction of any one from another.

6.3 Hardened grout

6.3.1 Hardened grout preparation

Fresh grout was prepared and filled in six 40*40*160 mm moulds (BS EN 196-1:2005) as follows. Fresh grout was taken from the mixer, stirred gently in a jug to become homogeneous, poured into the moulds, stirred and finished by a thin spatula. As the 18 grouts were chosen of high fluidity to produce concrete they did not vibrate in their moulds to avoid any segregation and bleeding agreeing with Domone and Jefferis (1994). Grout samples were left in their moulds for 24 hrs then removed from the moulds and immersed in water for 28 days (BS 4551 Part 1: 1998).

6.3.2 Grout flexure and compressive strength testing

After 28 days of water curing, grout samples were taken, wiped by clean cloth from water and any loose grits, and put in the testing machine in such way the load can be applied to the opposite faces as cast. Flexure strength of hardened samples was tested according to BS EN 196-1:2005 by the Instron machine at a rating speed of 1mm/min. Grout flexure and compressive strengths were calculated as the average of six samples.

The hardened grout prisms tested in flexure were broken into two halves each. A total number of twelve halves for each grout resulted and divided into two sets each contain six samples. One set was tested in the Instron machine for the compressive strength and the other set put into an oven to dry before sorptivity testing.

6.3.3 Grout Sorptivity testing

Sorptivity is one of hardened grout properties by which its water permeability can be measured and then, grout durability can be judged. Grout sorptivity was tested for the remained set from the flexure test, each mix consists of five halves not six. It was impossible to take six readings at the beginning of the test as the interval time was only 30 seconds. Samples were put in an oven at 105º C for 72 hours then, dry hot samples were removed from the oven and put into dry sealed container until they cooled (Dias, 2000; Khatib et al., 2010). After that, the vertical sides of each sample were sealed to yield uni-directional flow of water during the test and only the top and bottom surfaces were left uncovered. During the test, grout samples were weighed and put into a pan of about 2mm water height on their bottoms to allow the lower surface to absorb water as shown in Figure (6.11). Sample weight was then recorded at intervals up to 8 hours in order to get the amount of water adsorbed with time. Sorptivity of grout was calculated according to the following equation

$$i = St^{0.5} \tag{6.1}$$

where i is the increase in sample weight from the beginning of the test per unit area in contact with water (kg/m^2), t is the measured time in minutes at which the mass is measured, and S is the sorptivity in ($kg/m^2.min^{0.5}$) (Neville, 1995). Sample of sorptivity calculation is shown in Figure 6.12; the grout mix consists of S1, c/s of 1/0.9 and w/c of 0.50, sorptivity of grouts is shown in Table 6.2.

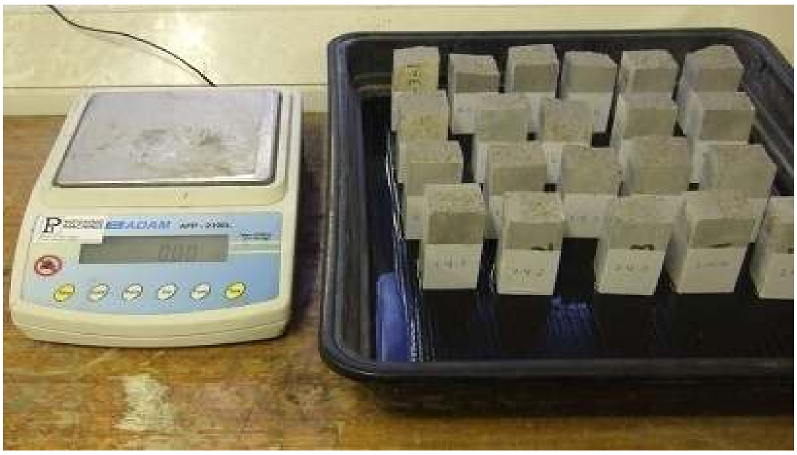


Figure 6.11 Hardened grout samples during the sorptivity test

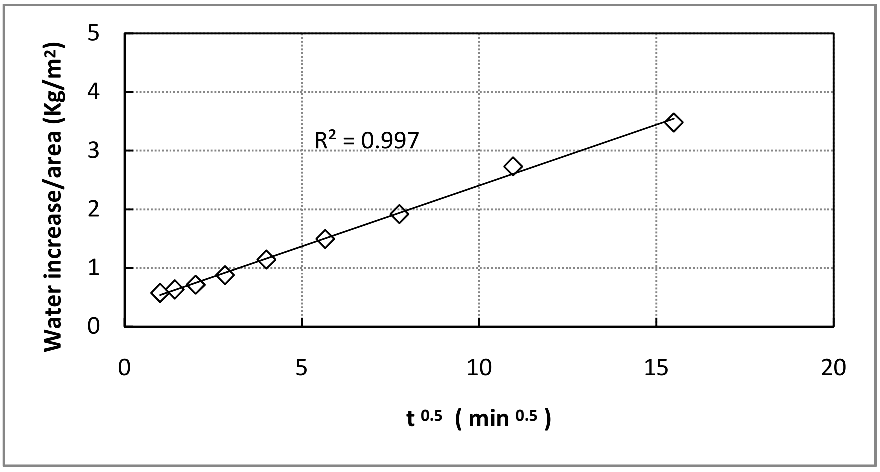


Figure 6.12 water increase per unit area vs square root of time in minutes

6.3.4 Mechanical properties of hardened grout

6.3.4.1 Effect of w/c ratio on the mechanical properties of grout

Figures 6.13 and 6.14 present the relations between grout flexure and compressive strength properties and w/c, respectively. Both mechanical properties of grout decrease with the increase in w/c ratio. Figure 6.13 shows that for grouts of c/s of 1/0.9 and the same w/c ratio, S3 grouts resulted in higher flexure strength than S1 grouts. For c/s of 1/0.6, S3 grouts exhibit the highest flexure strength and S1 grouts show the lowest values. The lower values of flexure strength of S1 grouts can be attributed to its smooth surface which results in weak bond under bending action during the flexure test between hardened cement paste and sand surface (Mehta, 1986). In addition, grouts at c/s of 1/0.9 show slightly higher flexure strength than those of c/s of 1/0.6 by using the same sand at the same w/c, and that could be attributed to the higher interlocking between sand particles at high sand quantity.

Table 6.2 Fresh grout bleeding and hardened grout properties test results

Mix No.	**Sand type**	**c/s ratio**	**w/c ratio**	**Flexure strength** (MPa)	**Compressive strength** (MPa)	**Sorptivity** $(kg/m^2.min^{0.5})$
1	S1	1/0.9	0.50	8.04	50.10	0.270
2	S1	1/0.9	0.45	9.16	57.61	0.196
3	S1	1/0.9	0.40	9.55	69.08	0.133
4	S1	1/0.6	0.45	8.49	47.96	0.270
5	S1	1/0.6	0.40	9.87	65.33	0.157
6	S1	1/0.6	0.35	11.22	72.99	0.092
7	S2	1/0.9	0.60	7.05	36.15	0.370
8	S2	1/0.9	0.55	7.64	38.58	0.330
9	S2	1/0.9	0.50	7.78	39.82	0.250
10	S2	1/0.6	0.50	7.84	43.18	0.288
11	S2	1/0.6	0.45	9.12	53.67	0.261
12	S2	1/0.6	0.40	10.11	57.57	0.130
13	S3	1/0.9	0.50	9.36	50.54	0.208
14	S3	1/0.9	0.45	10.96	59.27	0.136
15	S3	1/0.9	0.40	11.32	66.27	0.128
16	S3	1/0.6	0.45	9.79	51.28	0.203
17	S3	1/0.6	0.40	11.14	64.98	0.145
18	S3	1/0.6	0.35	12.00	68.05	0.109

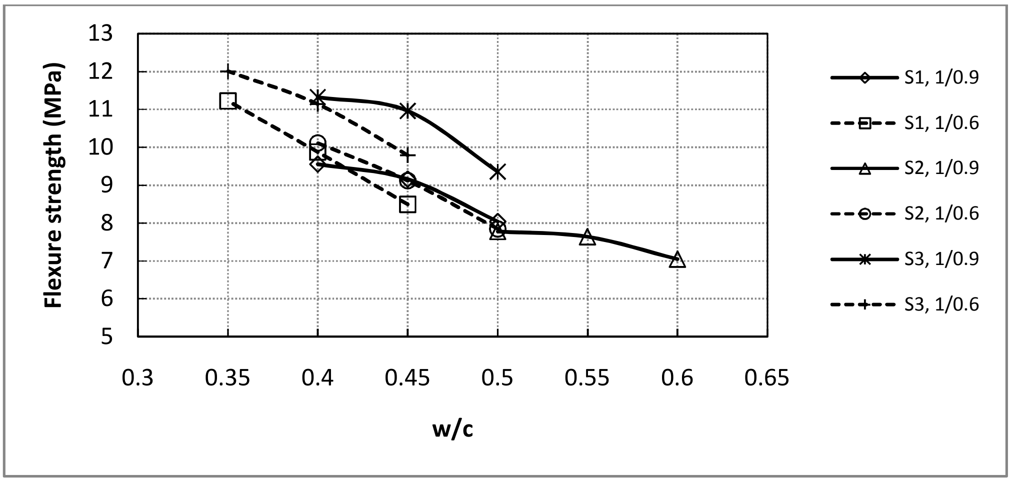


Figure 6.13 Grout flexure strength vs w/c at different c/s ratios

Figure 6.14 shows that, at high sand content of c/s of 1/0.9, S1 and S3 grouts have very similar compressive strength values. At w/c of 0.5 S2 grout shows less compressive strength than other sand grouts. Lower w/c ratios than 0.50 using S2 were not employed because the fluidity was not enough to produce PAC. The lower values of compressive strength of S2 grouts compared with other sand grouts could be attributed to the lowest excess paste resulted from filling its high aerated voidage and to give the grout its strength. At c/s of 1/0.6, S1 grout exhibits slightly higher compressive strength than S3 grout at w/c of 0.35 with close results at w/c of 0.40 and 0.45. In addition, sand effect on grout compressive strength at c/s of 1/0.6 is not high due to the large amount of excess paste volume at low sand content. In general, S1 and S3 show higher compressive strength than S2 grouts at the same water content due to the high voidage of S2 grouts which needs more paste to attain adequate workability and strength; similar results were reported by Cortes, et al., (2008). Although, at c/s of 1/0.9, S1 and S3 grouts show higher compressive strength than those for c/s of 1/0.6, S2 grouts show closer compressive strength at different sand contents.

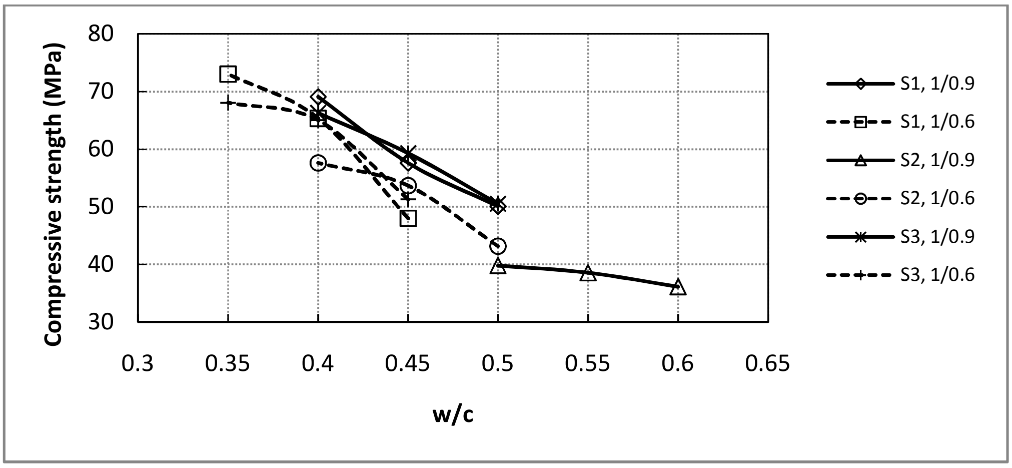


Figure 6.14 Grout compressive strength vs w/c at different c/s ratios

6.3.4.2 Relations between mechanical properties of grout and fresh grout flow time

Figures 6.15 and 6.16 show the relations between hardened grout flexure and compressive strengths and flow time of fresh grout, respectively. Both flexure and compressive strengths of grout increase with the increase in flow time in both cases of c/s ratios. Figure 6.15 illustrates that S3 grouts show the highest flexure strength and S2 grouts show the lowest values in both cases of sand contents. Consequently it can be concluded from these relations that, at a certain flow time S3 grouts show higher flexure strength than others, and that is of interest in the grout injection process through the coarse aggregate and the choice of sand in the production of PAC. As illustrated in Figure 6.16, S3 grouts have the highest compressive strength and S2 grouts show the lowest values in both cases of sand contents at the same flow time, however at the high flow time S1 resulted in the highest compressive strength grouts. This result is a reflection of water effect on flow-ability and strength as presented in Figure 6.14 where the highest compressive strength was resulted from S1 grouts especially at low w/c ratio.

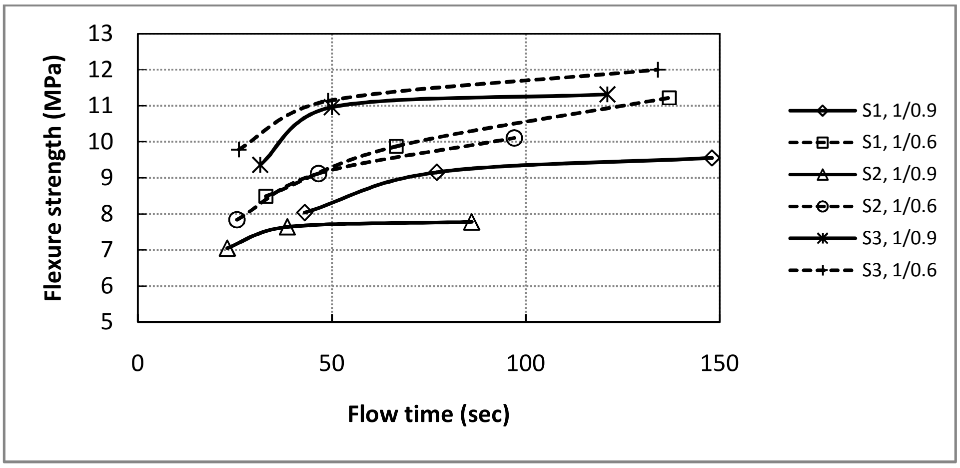


Figure 6.15 Flexure strength vs fresh grout flow factor at different c/s ratios

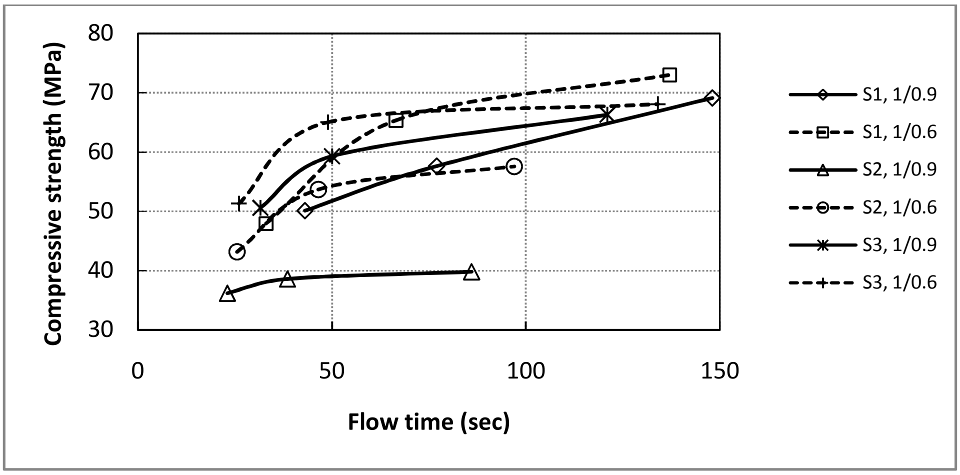


Figure 6.16 Compressive strength vs fresh grout flow time at different c/s ratios

6.3.4.3 Relations between mechanical properties of grout and fresh grout speed

Figures 6.17 and 6.18 illustrate the relations between grout flexure and compressive strength and its speed with the modified flow channel test in its fresh state, respectively.

Hardened grout flexure and compressive strength decrease with the increase in fresh grout speed. The decrease in hardened grout mechanical strength by increasing fresh grout speed is not more or less than a reflection of water effect on both speed and strength. At certain sand and cement contents, the water increase in grout increases its speed and decreases its strength as presented in section 6.3.4.1.

At the same flow speed and c/s ratio, S3 grouts show the highest flexure and compressive strength and S2 grouts show the lowest values in both cases of c/s ratios. Less difference at c/s of 1/0.6 was noticed because of high amount of cement paste which reduces the sand effect on strength. The advantages of these relations are in the choice of sand, which can be chosen by its grout strength at required workability, and that of course is useful in the grout injection process through the coarse aggregate and the resulting PAC.

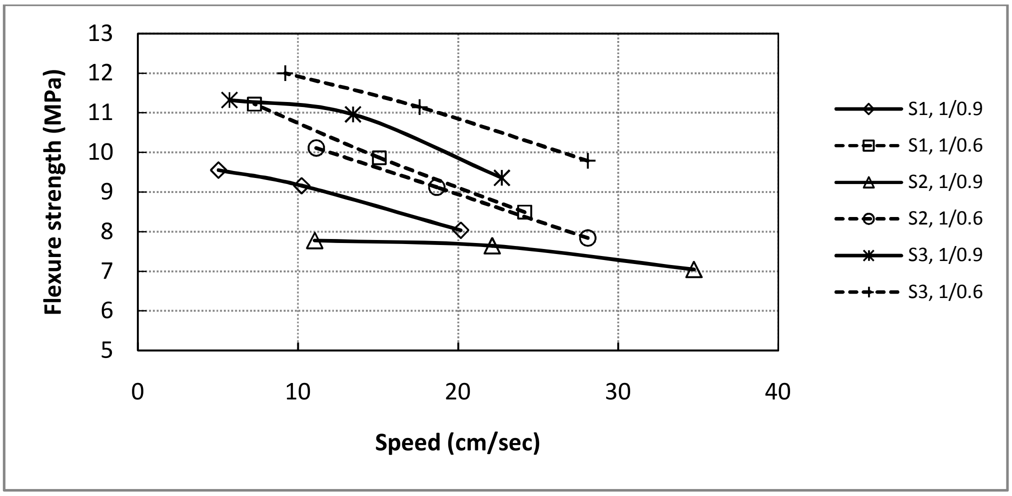


Figure 6.17 Flexure strength vs fresh grout speed at different c/s ratios

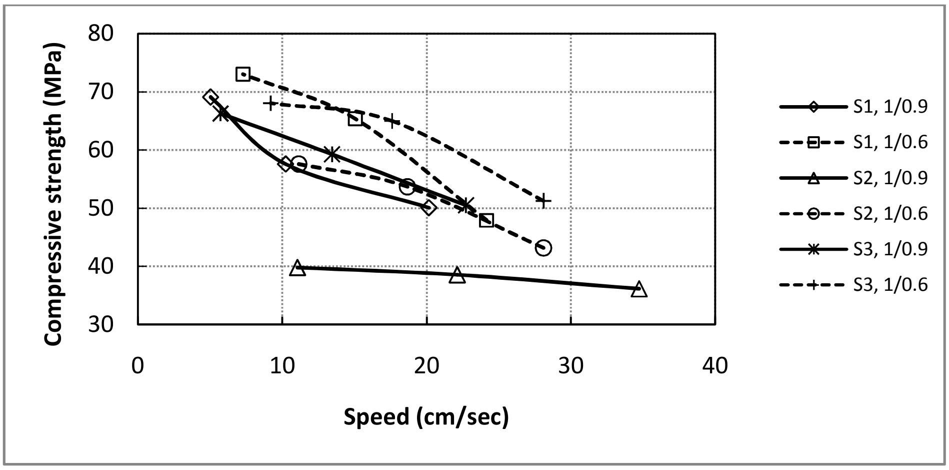


Figure 6.18 Compressive strength vs fresh grout speed at different c/s ratios

6.3.4.4 Relations between mechanical properties of grout and fresh grout plastic viscosity

Figures 6.19 and 6.20 illustrate the relations between grout flexure and compressive strength and its plastic viscosity parameter (*h*) in its fresh state, respectively. In both cases of c/s ratios grout mechanical strength increases with an increase in *h*. Moreover, at the same *h*, S3 grouts show higher flexure strength and S2 grouts show the lowest values in both cases of c/s ratios as shown in Figure 6.19. Figure 6.20 illustrates that for c/s of 1/0.9 grouts and the same *h*, S3 grouts show the highest compressive strength values and S2 grouts show the lowest values. At c/s of 1/0.6, S1 and S3 grouts show the same compressive strength at different viscosities and those are higher than resulted from using S2. Consequently, plastic viscosity is an important property of grout in its fresh state by which sand type can be chosen to give the required strength and that is advantageous in the design of grout as well as of PAC.

Relations between mechanical properties and *h* in Figures 6.19 and 6.20 show the same trends presented in Figures 6.15 and 6.16 between mechanical properties and flow time due to the correlation between *h* and flow time as presented in Figure 6.7.

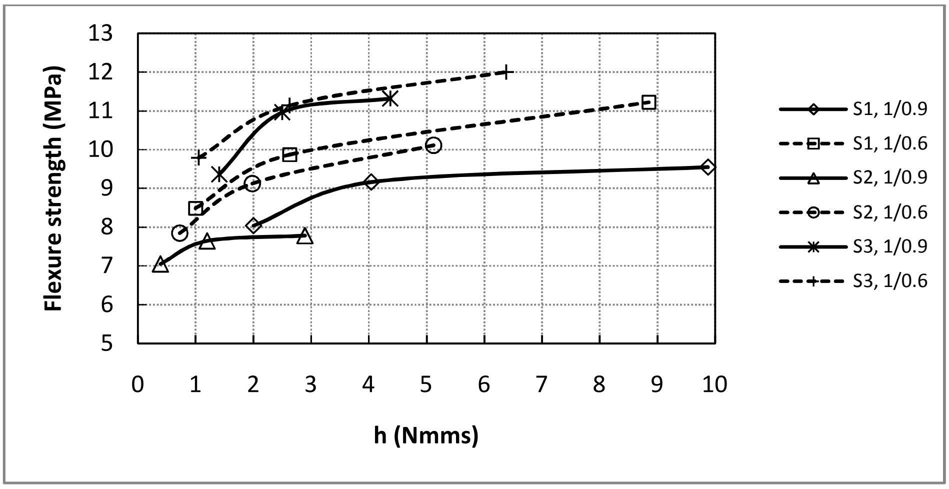


Figure 6.19 Flexure strength vs plastic viscosity at different c/s ratios

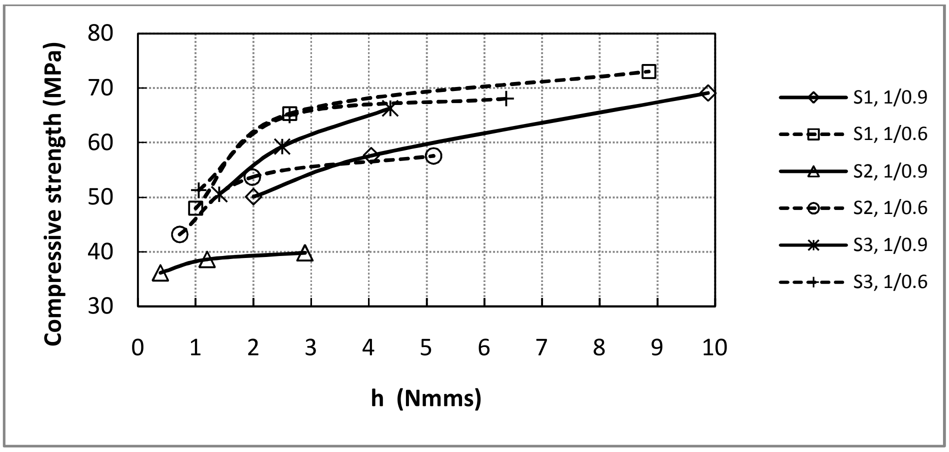


Figure 6.20 Compressive strength vs plastic viscosity at different c/s ratios

6.3.5 Sorptivity of hardened grout

6.3.5.1 Effect of w/c ratio on the sorptivity of grout

Figure 5.21 illustrates that grout sorptivity increases with an increase in w/c ratio for both cases of c/s ratios. This result was expected due to the increase of grout porosity by increasing water content and the same relation was presented by Huang (2001). At c/s of 1/0.9, S1 grouts show higher sorptivity than do S3 grouts at same w/c ratio. In addition, at w/c of 0.50, S2 grout presents lower sorptivity than S1 grout and higher than S3 grout and this can be attributed to the high bleeding rate of S1 grout as presented in Table 6.1. The high bleeding rate of S1 grouts means that excess water is trapped in the transition zone between sand particles and cement paste and consequently more volume of voids will be presented in the hardened grout and that increases grout sorptivity. Closer values of sorptivity using different sands were observed at c/s of 1/0.6 concluding that sand has less effect on sorptivity at lower contents. Consequently, sorptivity is controlled mainly by the high quantity of cement paste in grout at c/s of 1/0.6. As a result from this presentation, S3 is the best in respect to the resulting grout durability with the lowest water sorption at different w/c and c/s ratios.

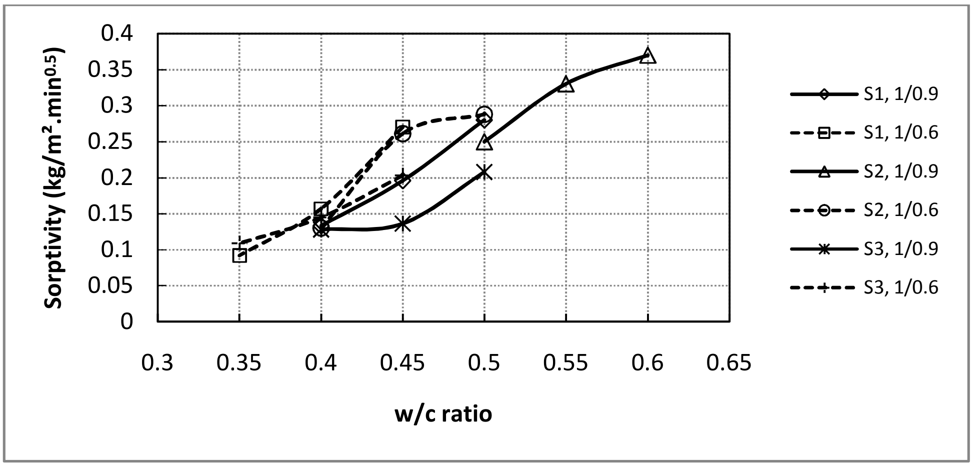


Figure 6.21 Grout sorptivity vs w/c ratio at different c/s ratios

6.3.5.2 Relations between hardened grout sorptivity and fresh grout flow time

Figure 6.22 illustrates the relations between hardened grout sorptivity and its flow time at c/s ratios of 1/0.9 and 1/0.6. Both cases of c/s ratios show a decrease in grout sorptivity as the flow time increases, and that is a reflection of the effect of water content in grout. In other words, the high flow time means grout has less water at constant cement and sand contents, which results in less pores inside the hardened grout and consequently less sorptivity. Although, S2 grouts show the highest sorptivity and S3 grouts show the lowest values in both cases of c/s ratios, at very high flow time, about 100 second and more at c/s of 1/0.6 all grouts show the same sorptivity. This is attributed to the low water content in grout which minimizes the capillary pores in hardened grout which decreases the sorptivity. The quality of sand required for grout durability can be chosen by this test where the lowest sorptivity at required workability can be identified and consequently the sand required can be chosen. As a result, S3 has resulted in lower sorptivity for flow time less than 100 seconds and S2 is the worst one.

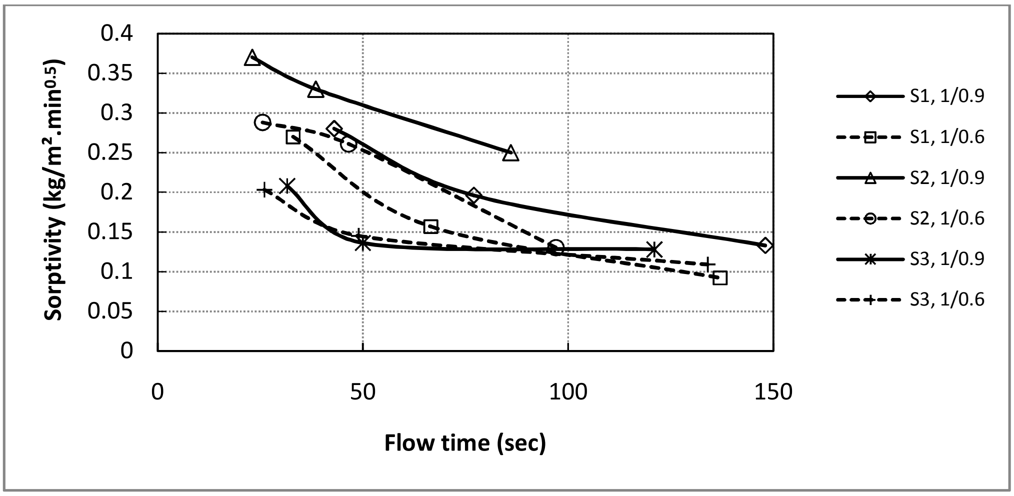


Figure 6.22 Grout sorptivity vs flow time at different c/s ratios

6.3.5.3 Relations between hardened grout sorptivity and fresh grout speed

Figure 6.23 presents the relations between hardened grout sorptivity and its fresh speed at c/s of 1/0.9 and 1/0.6. Water sorptivity of grout increases with the increase in fresh grout speed. It is a reflection of water effect as the increase in w/c ratio increases both grout sorptivity as presented in Figure 6.21and increases grout speed. For medium and high speed grouts, S2 grouts show the highest sorptivity and S3 grouts show the lowest ones at the same c/s ratio. The high sorptivity resulted from S2 grout is a reflection of water effect as presented in Figure 6.21. On the other hand, at very low speed around 10 cm/s and less especially at c/s of 1/0.6, grouts show closer sorptivity values due to the low w/c which means grouts have closer volume of voids.

At certain fresh grout speed, hardened grout of S3 has resulted in the lowest sorptivity, and this is an advantage of the choice of sand type.The same result was presented previously with the w/c and the flow time test results, sections 6.3.5.1 and 6.3.5.2.

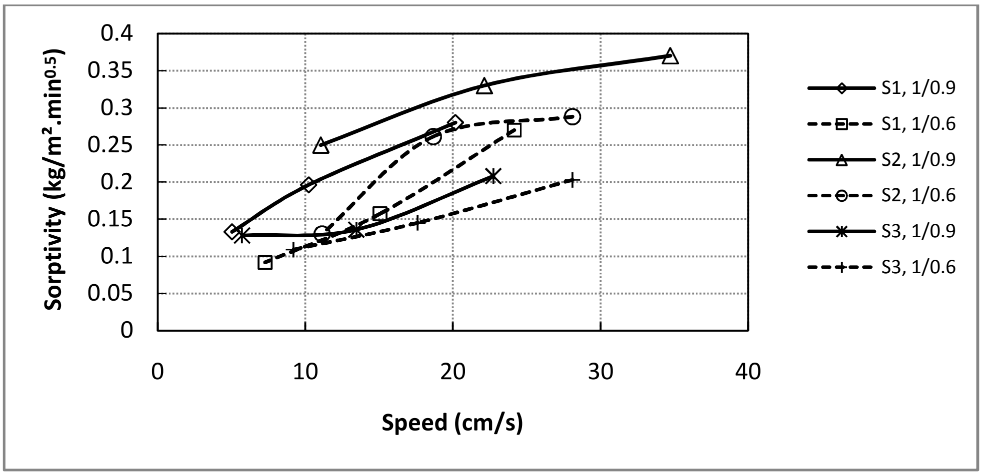


Figure 6.23 Grout sorptivity vs grout speed at different c/s ratios

6.3.5.4 Fresh grout plastic viscosity and hardened grout sorptivity

As the plastic viscosity of grout is one of the fresh grout properties, its relation to the sorptivity was investigated as shown in Figure 6.24 at c/s ratios of 1/0.9 and 1/0.6. From the curves illustrated, it is clear that grout sorptivity decreases with an increase in *h* for both cases of c/s ratios. This is a reflection of the effect of w/c ratio on grout viscosity as presented in Figure 6.2 where grout viscosity decreases with an increase in w/c ratio. Curves show that, at the same *h*, S2 grouts present the highest sorptivity values and S3 grouts show the lowest values concluding that S3 is the best to produce durable grouts. At c/s of 1/0.6, grouts show closer sorptivity especially at high *h* values. The effect of sand quantity on grout sorptivity at certain *h* suggests that, c/s of 1/0.9 resulted in higher grout sorptivity than c/s of 1/0.6 for S1and S2. On the other hand, S3 grouts show closer sorptivity values at different c/s ratios with the lowest values which advantageously suggested its use in grout production for durability purposes.

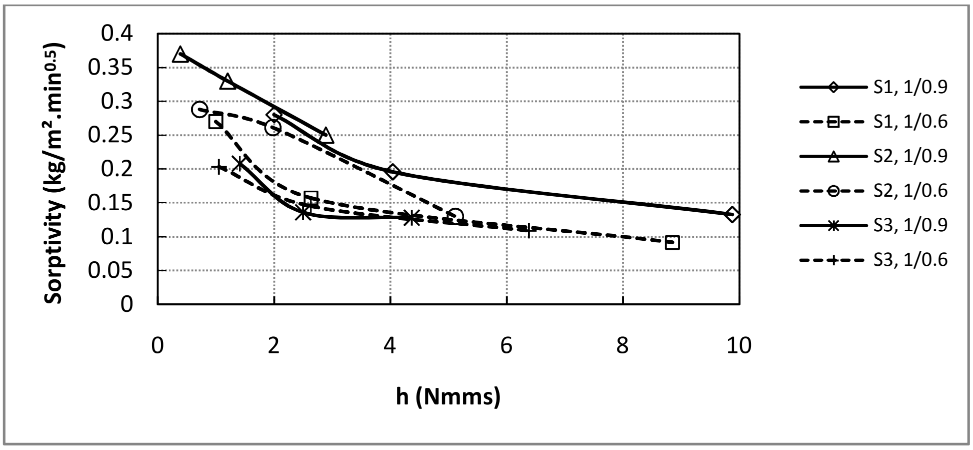


Figure 6.24 Grout sorptivity vs plastic viscosity at different c/s ratios

6.4 Correlation between hardened grout properties

It is of interest to investigate the relations between different grout properties in grout hardened state like, flexure strength, compressive strength and sorptivity as that will lead to predict each one from another. Although grout strength is directly related to the porosity of grout and the sorptivity is a function of pore size distribution, good correlation exists which can only be considered a first estimation. Correlations between different hardened grout properties are presented below.

6.4.1 Relation between compressive and flexure strengths of grout

Figure 6.25 shows the relation between compressive strength and flexure strength for all grouts using different types and contents of sand. Compressive strength of grout increases with the increase in its flexure strength. The same trend was reported by Atis, (2002) in the relation between flexure and compressive strengths of workable concrete. As shown, a good correlation with R^2 of 0.82 was found in the relation between compressive and flexure strengths despite the difference in sand type as follow;

$$f_g = 3.43 * f_t^{1.232} \tag{6.2}$$

where f_g is the compressive strength of grout in the range of 36.15 to 73 MPa and f_t is the flexure strength in the range of 7.05 to 12 MPa.

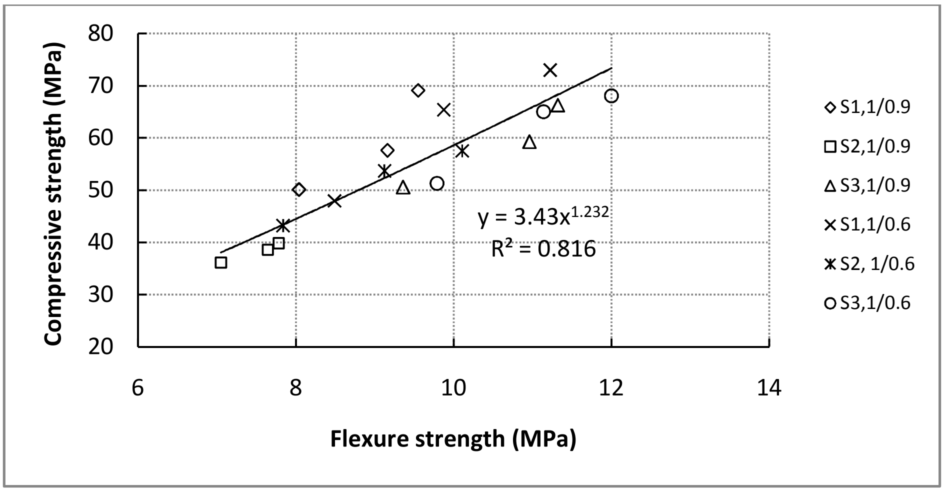


Figure 6.25 Compressive strength vs flexure strength for all grouts

A comparison between Equation 6.2 resulted from the present study and that presented from Abdelgader 1995 data is presented in Figure 6.26. It is shown that, at the same grout flexure strength, grout compressive strength presented from this study is higher than that of Abdelgader study. The high difference in grout compressive strength increases as the flexure strength increases can be attributed to the direct effect of sand type because of the bond effect between aggregate particles and cement paste. More specific, at low flexure strength lower difference in grout compressive strength suggesting that the sand used by Abdelgader is similar as S2 used in the present investigation at high content as presented in Figure 6.25 for S2 at c/s of 1/0.9.

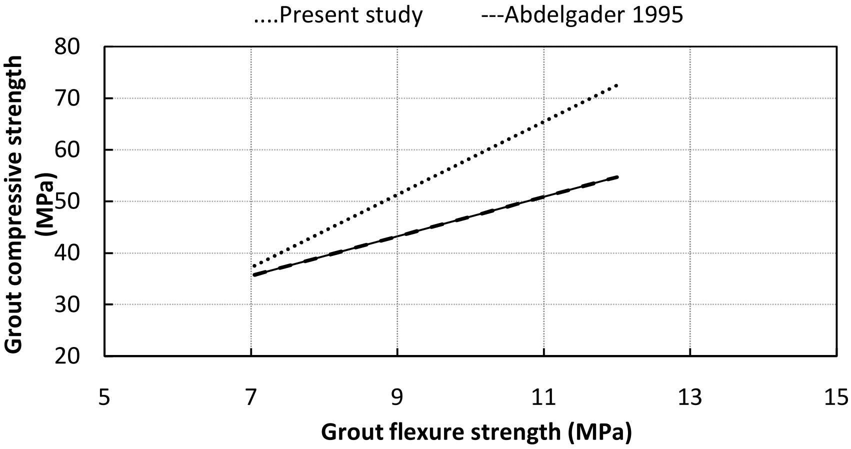


Figure 6.26 Grout compressive-flexure strength relation comparison between Abdelgader 1995 study and the present study

6.4.2 Relation between grout sorptivity and flexure strength

Figure 6.27 shows the relation between sorptivity and flexure strength for all grouts using different sand types and contents. Non linear relation of good correlation coefficient of 0.86 was found between grout sorptivity and flexure strengths as follows;

$$S_g = 43.36 * f_t^{-2.42} \tag{6.3}$$

where S_g is the grout sorptivity in the range of 0.092 to 0.37 $(kg/m^2.min^{0.5})$ and f_t is the flexure strength in the range of 7.05 to 12 MPa.

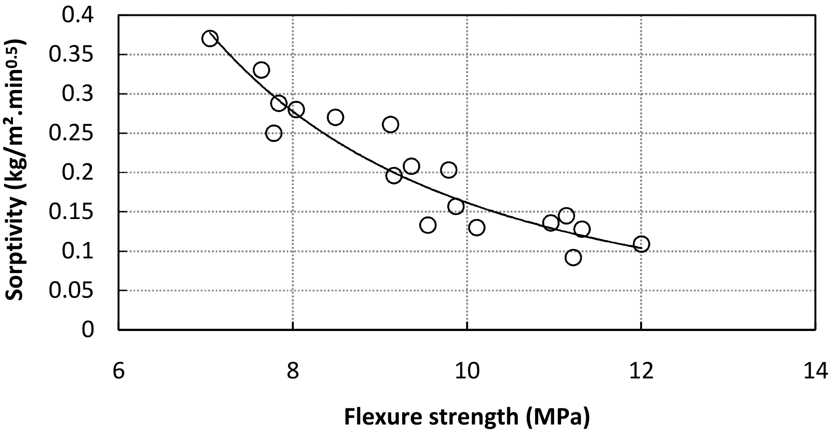


Figure 6.27 Sorptivity vs flexure strength for all grouts

6.4.3 Relation between compressive strength and sorptivity

Figure 6.28 shows the relation between sorptivity and compressive strength for all grouts using different types and contents of sands. As shown in the figure a good correlation with R^2 of 0.85 was found between grout sorptivity and compressive strength as follows;

$$S_g = -\,0.006 * f_g \ + 0.57 \tag{6.4}$$

where S_g is the grout sorptivity in the range of 0.092 to 0.37 ($kg/m^2.min^{0.5}$) and f_g is the compressive strength in the range of 36.15 to 73 MPa.

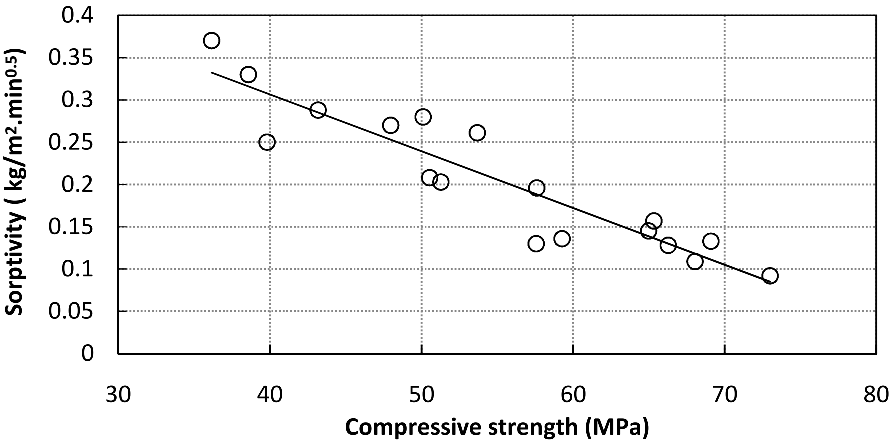


Figure 6.28 Sorptivity vs compressive strength for all grouts

6.5 Conclusions

Eighteen grouts of enough flow to produce PAC were prepared in which, three different sands at three w/c ratios and two c/s ratios, 1% of SP was employed with partial replacement of cement with Pfa of 20%. After that, grout fresh properties were measured, the effect of different factors on the rheology of fresh grout then analyzed and the relations between fresh and hardened properties were also investigated. Finally, the correlation between different hardened grout properties was studied such as, flexure strength and compressive strength and sorptivity. The following conclusions can be drawn:

- Grout water bleed increases with an increase in w/c ratio for all grouts using different sands. The finest sand S2 results in lower bleeding at the same w/c ratio and the coarsest sand S1results in higher water bleed. Moreover, at the same w/c ratio and the same sand, grouts of high sand content of c/s of 1/0.9 resulted in lower water bleed than those of lower sand content of 1/0.6.

- Grout plastic viscosity parameter can be predicted from its flow time and its speed through the flow meter channel. Moreover, the modified flow meter test shows higher sensitivity than the flow funnel test especially for high viscosity grouts however, the flow cone and modified flow meter tests can be used to assess medium and high flow grouts. They are very useful in the field work where the rheology testing devices are not applicable.
- Hardened grout flexure and compressive strengths decrease with an increase in w/c ratio while grout sorptivity increases.
- S3 grouts show higher flexure strength than S1 grouts in both cases of c/s ratios due to the smooth surface of S1 which weakens the bond between the paste and sand particles under bending action. In addition, grouts at c/s of 1/0.9 show slightly higher flexure strength than those of c/s of 1/0.6 by using the same sand at the same w/c, and that could be attributed to the higher interlocking between sand particles at high sand quantity.
- S1 and S3 grouts demonstrate close compressive strength values for both cases of c/s ratios due to the closer voidage of both sands where S2 grouts show lower compressive strength. Although, at c/s of 1/0.9, S1 and S3 grouts show higher compressive strength than those for c/s of 1/0.6, S2 grouts show closer compressive strength at different sand contents.
- The lower values of flexure and compressive strengths of S2 grouts compared with others at the same w/c and c/s ratios can be attributed to its high voidage which consumes more paste to fill up the voids and to the high surface area which needs more paste to bond sand particles and give the grout its strength.

- At the same grout consistency using speed, flow time and plastic viscosity tests, S3 grouts show the highest flexure and compressive strengths and the lowest sorptivity. On the other hand, S2 grouts show the lowest flexure and compressive strengths and the highest sorptivity. And that difference is clearer at c/s of 1/0.9 than c/s of 1/0.6 because of the high volume of cement paste at low sand content concluding that prediction of hardened grout properties from fresh grout rheology is not confidential at low sand content.
- At c/s of 1/0.9, S1 grouts show higher sorptivity than do S3 grouts at the same w/c ratio due to the high bleeding rate of S1 grouts. The high bleeding rate of S1 grouts results in more voids in the transition zone of the hardened grout and that increases grout sorptivity. Closer values of sorptivity using different sands were observed at c/s of 1/0.6 concluding that sand type has less effect on sorptivity at lower contents. For durability purposes, S3 seems to be the best because its grout gave the lowest water sorption especially at intermediate w/c ratios at high sand content.
- Good correlation was found between flexure and compressive strengths using different sands at different w/c and c/s ratios, and the resulted relation can be used in the prediction of any one from the other in the tested range.
- Although grout strength is directly related to the total volume of voids in grout and the sorptivity is a function of pore size continuity, a good correlation between strength and sorptivity was found, which can only be considered a first estimation in the prediction of grout strength from its sorptivity.

CHAPTER 7: EFFECT OF GROUT ON CONCRETE PROPERTIES AND CORRELATION BETWEEN CONCRETE PROPERTIES

7.1 Introduction

As the effect of different mix ingredients on hardened grout properties were investigated in chapter 6, the effect of hardened grout on the properties of PAC will be presented in this chapter. Knowing the relations between hardened grout and PAC will help in prediction of concrete properties from work on grout, and that consequently will minimize the lab work. The effect of w/c ratio on the compressive strength and sorptivity of PAC will be investigated.

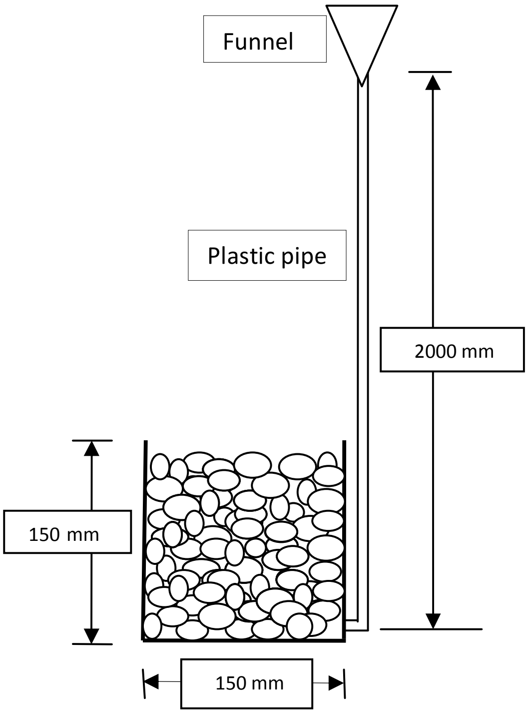
In the investigation, a total number of 18 grout mixes were produced as presented in section 6.1 and Table 6.1 and used to produce PAC. A total number of 180 concrete cubes were prepared; ten cubes for each mix, five cubes for compressive strength and five cubes for sorptivity test. According to the grout mix design presented in chapter 6, three sands were chosen, S1, S2 and S3 at c/s of 1/0.9 and 1/0.6 and three different w/c ratios according to the ability of each grout to penetrate through the coarse aggregate mass. SP was chosen as a chemical admixure at 1% and 20% of the cement was replaced by Pfa as a mineral additive.

7.2 Concrete Casting and testing

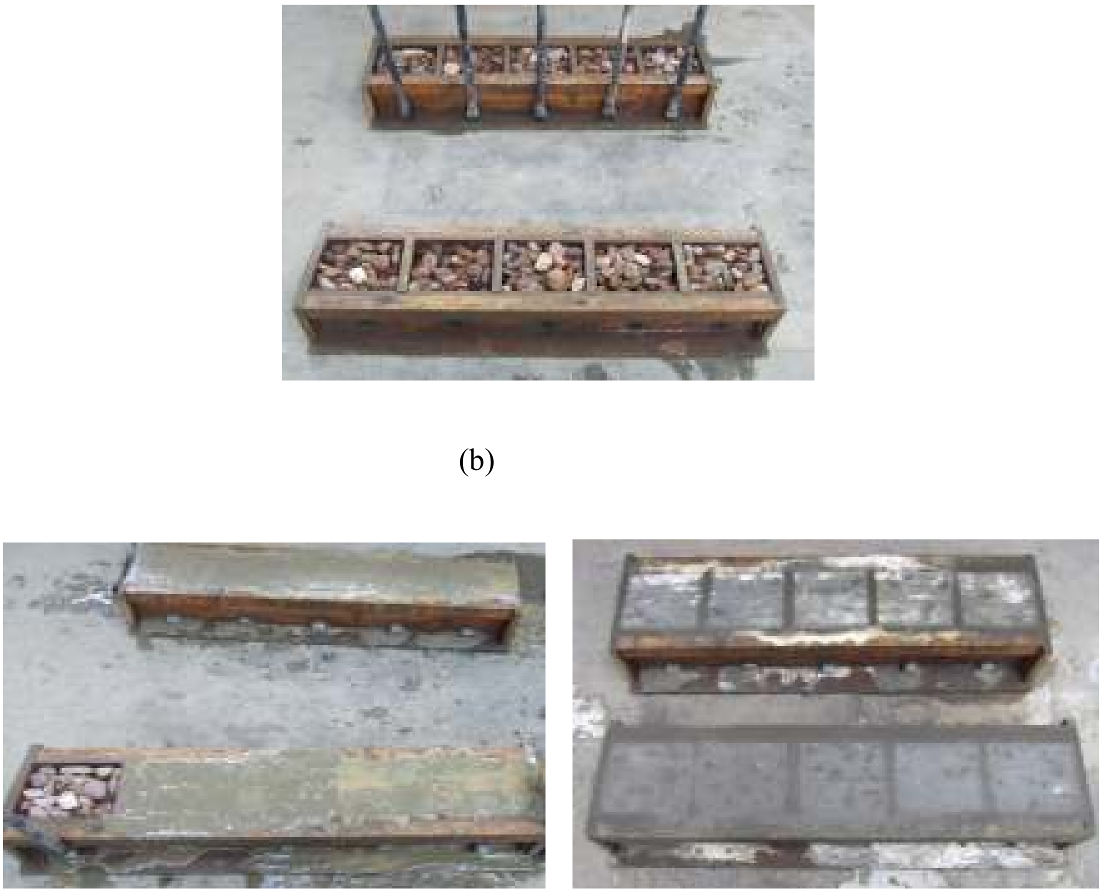
7.2.1 Concrete casting

For concrete compressive strength and sorptivity testing, 150 mm cubic moulds were used; five samples for compressive strength and five samples for sorptivity. Ten moulds were prepared in such way that grout can be injected from their lower side as shown in Figures 7.1(a) and (b) to assure good quality of PAC produced. Grout injection in the production of PAC should be implemented from underneath of the coarse aggregate skeleton to avoid any trapped air during the grouting process (Littlejohn, 1984; ACI 307.1R, 1997). Figures 7.1(b), (c) and (d) are images showing PAC production process.

To insure that full penetration was achieved by the grout through the coarse aggregate skeleton voids, at 28 days PAC cubic sample was cut into two pieces. It was found that the grout penetrated all the coarse aggregate voids without any honeycombing and the concrete is homogeneous as shown in Appendix C.



(a)



(b)

(c) (d)

Figure 7.1 PAC production process

(a) Schematic diagram of PAC injection. (b), (c) and (d) Images of PAC production

7.2.2 Concrete compressive strength testing

PAC compressive strength is measured as it gives an overall picture of the quality of concrete (Neville, 1995 and Mehta, 1986). After 28 days of curing, ten concrete cubes were removed from water and wiped by a cloth. Five cubes were taken to measure the compressive strength of concrete and the other five put into an oven to dry and prepared for the sorptivity test. The compressive strength of concrete was calculated as the ultimate compressive load registered by the compression machine divided by the area of the cube (BS 1881-116, 1983). The final compressive strength of concrete is the average of five samples.

7.2.3 Concrete sorptivity testing

Sorptivity test determines the rate of water absorbed by capillary action in concrete sample. In addition, it measures the rate of water absorption by capillary suction of unsaturated concrete put in contact with water without pressure (Neville, 1995). The importance of this test is that it can be considered as an indication of water permeability in concrete and consequently concrete durability can be judged. And this is important for PAC as it has been used widely for underwater reinforced concrete structures.

For sorptivity test, five concrete cubes were put in an oven at 105 degrees centigrade for 72 hours (Dias W. 2000). After that, hot samples were removed from the oven and put into dry sealed containers until they cooled. Following that, concrete lower sides were sealed by a tape to prevent any water from touching them during the sorptivity test; the bottom surface of the sample was left uncovered. Concrete samples were weighed and put into a pan of about 2mm water high on small supports, to allow the lower surface to absorb water as shown in Figure 7.2. Finally, sample weight then recorded at intervals up to 8 hours. A digital balance with maximum capacity of 15 Kg and ± 5 gm accuracy was used in concrete weight measuring. Time was measured by a stop watch. Sorptivity was calculated as presented in section 6.3.3. A sample of sorptivity calculation is shown in Figure 7.3 for grout of S1, c/s of 1/0.9 and w/c of 0.50; in this sample, concrete sorptivity is 0.12 $kg/m^2.min^{0.5}$.

Figure 7.2 PAC during the sorptivity test

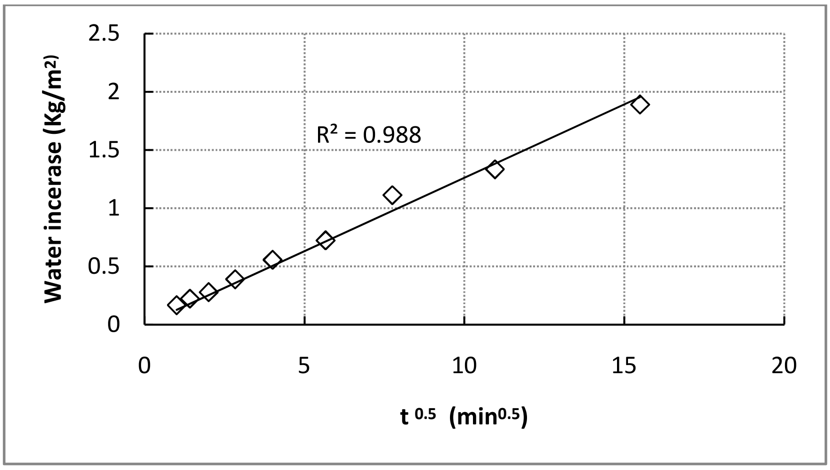


Figure 7.3 Increase in water mass per unit area of PAC and square root of time

7.3 Effect of w/c ratio on the properties of PAC

7.3.1 Effect of w/c ratio on compressive strength of concrete

Figure 7.4 shows the relation between PAC compressive strength and w/c ratio at c/s ratios of 1/0.9 and 1/0.6. Concrete compressive strength decreases with the increase in w/c ratio for both cases of c/s ratios. Concrete produced from S1 shows the highest compressive strength values at the same w/c ratio and S2 resulted in the lowest compressive strength concrete showing a reflection of grout compressive strength presented in section 6.3.4.1. High difference in concrete compressive strength between S1 and S3 grouts can be seen at low water contents, and closer strength values are noticed at high water content for both cases of c/s ratios. At c/s of 1/0.6 and w/c of 0.45 all sand grouts present the same concrete strength indicating that sand type effect on PAC compressive strength has eliminated. Moreover, S1 and S3 grouts show the same concrete compressive strength at w/c of 0.5. The same compressive strength using different sands at high w/c is attributed to the high cement paste volume which enough to fill up the sand voids and separate its particles and eliminate the sand effect on concrete compressive strength.

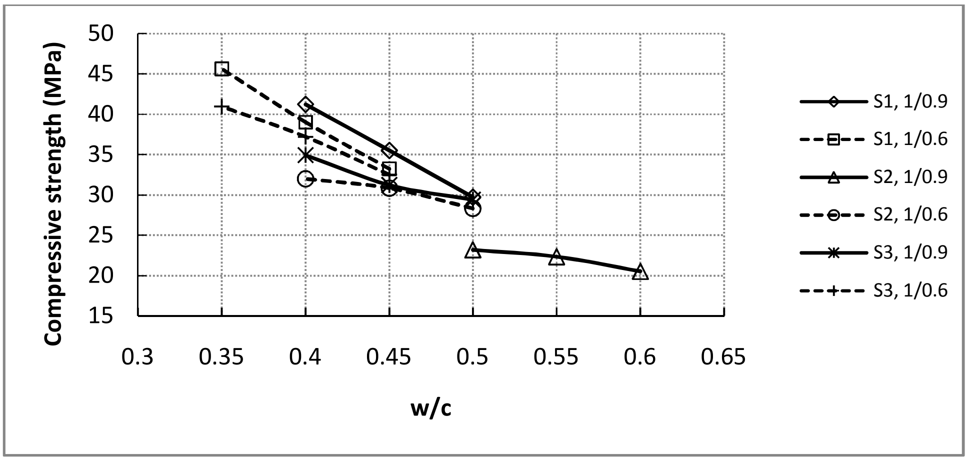


Figure 7.4 Concrete compressive strength vs w/c at different c/s ratios

7.3.2 Effect of w/c ratio on the sorptivity of concrete

Figure 7.5 illustrates that PAC sorptivity increases with the increase in w/c ratio for both cases of c/s ratios. This trend was expected due to the increase of grout porosity by increasing water contents. Concrete produced from using S1 grouts shows the lowest sorptivity values than those resulted from S2 and S3 grouts at c/s of 1/0.9, and that is attributed to the better grout penetration resulted by S1 grouts. Although S3 grouts presented the lowest sorptivity especially at high sand content as presented in section 6.3.5.1, Figure 6.21, S1 concrete shows the lowest sorptivity as presented in Figure 7.5, suggesting that S3 concrete could contains higher voids in the transition zone between coarse aggregate and grout than S1 concrete.

At c/s of 1/0.6, S2 concretes show the highest sorptivity and S1 concretes show the lowest ones due to the high sorptivity of S2 grouts as presented in section 6.3.5.1. The high sorptivity resulted from using S2 was expected because it is the finer size with larger surface area, and that results in higher volume of voids in the transition zone between sand particles and cement paste in grout. The same result was reported by Al-Harthy et al. (2006), who noticed that, as the fine sand quantity in concrete increases the resulting concrete water absorption increases.

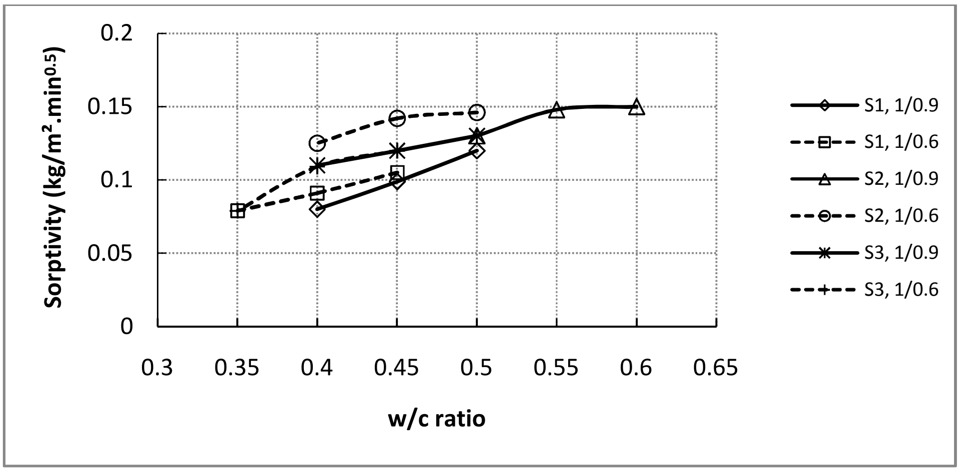


Figure 7.5 Concrete sorptivity vs w/c at different c/s ratios

7.4 Correlation between hardened grout and concrete properties

As PAC production mainly depends on the grout injected through the coarse aggregate, consequently PAC properties will be affected by the injected grout properties. This part investigates the effect of hardened grout properties on the produced PAC properties where the relations between hardened grout and concrete properties will be studied.

7.4.1 Compressive strength of PAC and compressive strength of grout relations

A good linear correlation with a coefficient of 0.86 was found between PAC compressive strength and grout compressive strength as shown in Figure 7.6 for all grouts. As a result, a relationship between grout compressive strength and concrete compressive strength can be derived as follow:

$$f_{cu} = 0.55 * f_g + 2.09 \tag{7.1}$$

where f_{cu} is the compressive strength of concrete in the range of 22.34 - 45.6 MPa and f_g is the grout compressive strength in the range of 36.15 –72.99 MPa. According to this relation, PAC compressive strength at 28 days can be predicted by knowing the making grout compressive strength using rounded coarse aggregate. The line graph shows also that grout compressive strength always higher than that of PAC, and that because of concrete compressive strength is affected adversely by the bond between hardened grout and coarse aggregate as reported by Rao and Prasad (2002) for normal concrete.

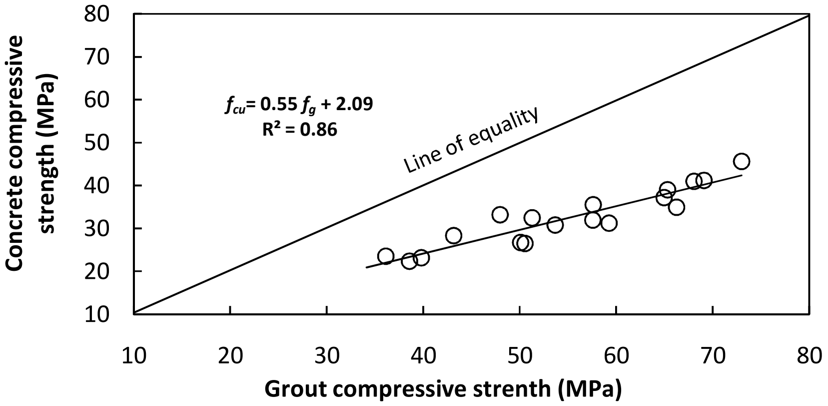


Figure 7.6 Concrete compressive strength vs grout compressive strength

A comparison between equation 7.1 developed in the current investigation and equation 2.5 presented by Abdelgader (1995) was made as shown in Figure 7.7. As presented in the graph, at the same grout compressive strength PAC resulted from the present study shows lower values of compressive strength than those calculated by equation 2.5 presented by Abdelgader (1995). This can be attributed mainly to the bond between coarse aggregate and grout. In other words, the bond between grout and coarse aggregate in this study is lower. This may be due to the better quality of grout produced by Abdelgader using very high shear mixer where high cement particle dispersion occurred in the fresh grout which gives higher bond between the grout and the coarse aggregate. This difference in concrete strength could be recognized also to the rougher coarse aggregate surface used by Abdelgader (1995) which gave better bond between grout and aggregates. It was also noticed that, at higher grout compressive strength the compressive strength of concrete deviates from the equality line due to the high coarse aggregate stress concentration as the stresses transferred through the coarse aggregate as reported by Abdelgader and Gorski (2001). Rao and Prasad (2002) reported that, at certain mortar strength the bond strength in the transition zone between mortar and coarse aggregate depends of the roughness of coarse aggregate. Consequently, the difference in aggregate roughness used in both investigations is most likely behind the difference in PAC strength at the same grout strength.

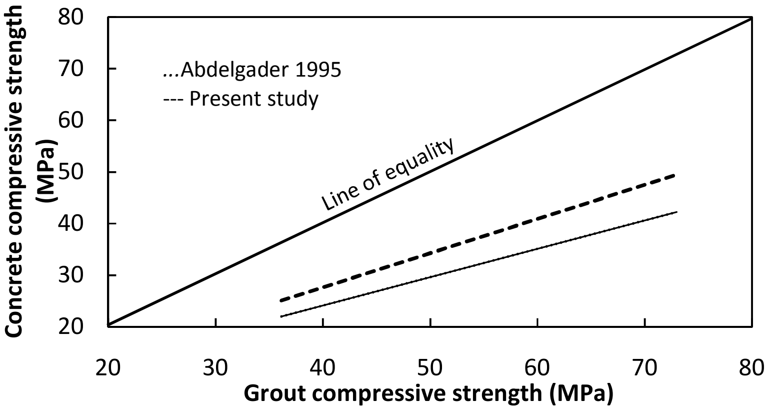


Figure 7.7 Concrete compressive strength comparisons between Abdelgader study, 1995 and the present study.

7.4.2 Sorptivity of concrete and sorptivity of grout relations

Concrete sorptivity increases with the increase in grout sorptivity as shown in Figure 7.8. Linear correlation with a coefficient of 0.75 was found as anticipated because of the role of grout on concrete properties. Other factors like coarse aggregate properties and the bond between aggregate and grout have also an effect on the resulted relation. According to this relation, PAC sorptivity can be predicted from its grout sorptivity, and this is useful for small scale testing, as PAC sorptivity can be calculated from working on grout only. It is clear that PAC sorptivity is lower than that of grout due to the effect of coarse aggregate which has very low water absorption as presented in section 5.2. In addition concrete and grout show very close values at very low sorptivity near the equality line as presented in Figure 7.8.

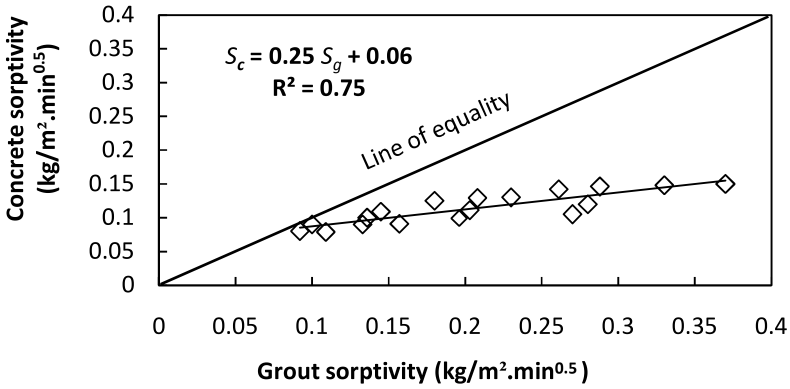


Figure 7.8 Concrete sorptivity vs grout sorptivity

7.5 Relations between w/c ratio and concrete-grout (C/G) properties

7.5.1 Relation between w/c ratio and concrete-grout compressive strength ratio

Figure 7.9 shows the relation between C/G compressive strength ratio and w/c ratio at c/s of 1/0.9 and 1/0.6 using different sand types. Apparently, PAC compressive strength is lower than that of grout for all mixes due to the stress concentration on the coarse aggregate particles as reported by Abdelgader and Gorski (2001). At the same w/c ratio, the higher values of C/G ratios generally obtained by using c/s of 1/0.6 for the same sand. The high ratio of C/G for c/s of 1/0.6 grouts can be certified to the high cement paste content in grout where the paste was enough to cover sand particles and improve the bond between the grout and the coarse aggregate. Moreover, the highest C/G strength ratios were presented by using S1 in grout for both cases of c/s ratios due to its lowest voidage and surface area and consequently highest inter-particle distance. Although the decrease in strength ratio at very low w/c ratios between 0.35 and 0.4, the general trend shows that as the w/c ratios increase, the C/G increases due to the higher relative effect on grout strength than concrete by increasing water content because greater amount of entrapped air in grout than concrete (Neville, 1995).

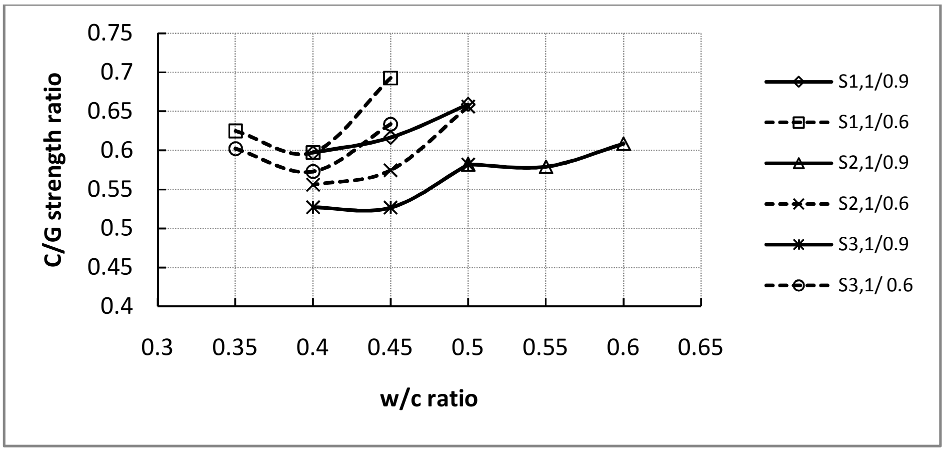


Figure 7.9 Concrete-grout compressive strength ratio vs w/c ratio

7.5.2 Relation between w/c ratio and concrete-grout sorptivity ratio

Figure 7.10 shows the relation between C/G sorptivity ratio and w/c ratio at c/s of 1/0.9 and 1/0.6 using different sand types. This figure indicates that concrete sorptivity is lower than that of grout with ratio less than 1.0 because of the coarse aggregate consequences which minimizes concrete sorptivity. C/G sorptivity ratio decreases with the increase in w/c ratio due to the direct increase in grout voids by rising water content. In other words, the relative low concrete sorptivity values compared with that of grout at high water contents could be accredited to the effect of coarse aggregate which decreases the rate of concrete sorptivity at constant decrease rate in grout sorptivity. In addition, the high amount of coarse aggregate particles in PAC makes many obstacles to the water transmission through the grout and that may reduce the sorptivity of concrete compared with grout.

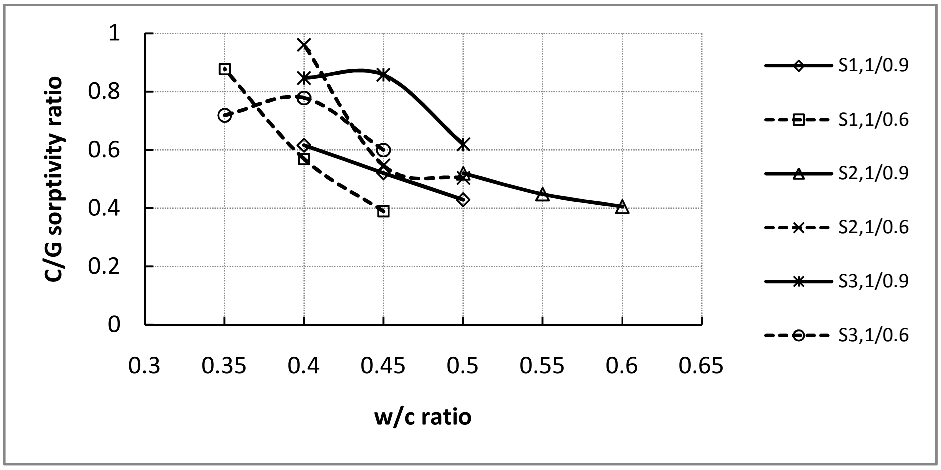


Figure 7.10 Concrete-grout sorptivity ratio vs w/c

7.6 Relation between compressive strength and sorptivity of PAC

Relations between concrete compressive strength and sorptivity for c/s of 1/0.9 and 1/0.6 are presented in Figure 7.11. Both cases of c/s ratios show that concrete compressive strength decreases with an increase in sorptivity. This is attributed to the increase in concrete porosity which adversely affected on concrete compressive strength. Similarly, Joseph and Ramamurthy (2009) reported that the compressive strength and resistance to capillary suction of concrete correlates fairly well. Neville (1995) reported that, concrete compressive strength decreases with the increase in its porosity. Although, sorptivity means the continuity of pores inside the concrete to ensure water transmission, these pores are part of volume of voids which affects on concrete compressive strength, this can be considered as a first estimation.

High sorptivity values were observed for S2 grouts and that is accompanied with low compressive strength where S1 and S3 grouts show relatively closer values of high compressive strength accompanied with low sorptivity for both cases of c/s ratios.

Linear relationship between concrete compressive strength and sorptivity was found from combining all samples in one curve despite sand type and content with coefficient of correlation of 0.84 as shown in Figure 7.11. This relationship has been derived for compressive strength in the range of 20.51 to 45.6 MPa and sorptivity of 0.079 to 0.15 $kg/m^2.min^{0.5}$. The following equation can be drawn from the relation between concrete compressive strength and sorptivity;

$$S_c = -0.003 \ f_{cu} + 0.22 \qquad (7.2)$$

where S_c is the concrete sorptivity ($kg/m^2.min^{0.5}$) and f_{cu} is the compressive strength (MPa) of concrete.

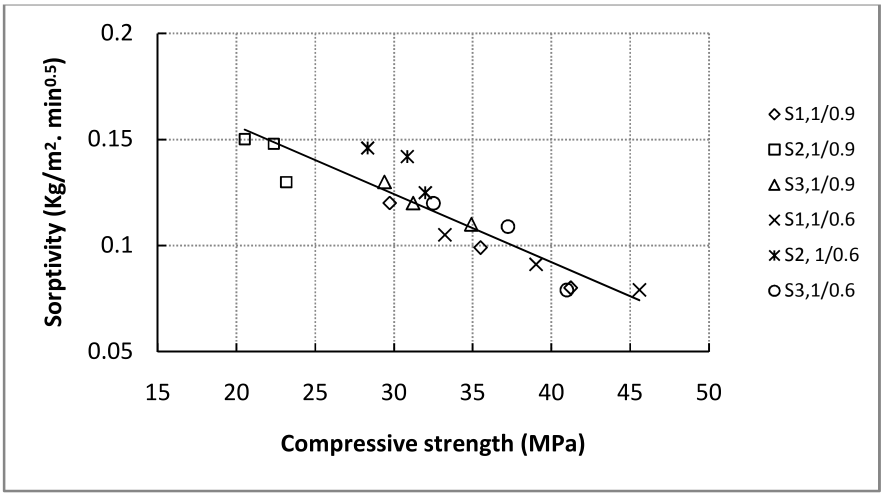


Figure 7.11 Concrete sorptivity vs concrete compressive strength at different c/s ratios

Comparisons between sorptivity-compressive strength relations obtained in this study for PAC and those from different studies for normal (NC) and self compacting concretes (SCC) are presented in Figure 7.12, (Liu, 2010; Khatib J and Clay R, 2003; Zhu W. and Bartos P., 2003; Bai J, Wi;d S. and Sabir, B., 2002; and Dias W., 2000). The relations show that, at the same compressive strength, sorptivity of PAC is the lowest compared with SCC and NC in most cases. Data presented by Liu (2010) for SCC shows lower sorptivity than PAC because of the higher amount of Pfa used in the mix, with percentages of 40% and 60%. The increase in fly ash percentage in concrete decreases the sorptivity as reported by Gopalan (1996), Liu (2010) and Zhu and Bartos (2003). Consequently, PAC has a good water permeability resistance comparing with other concretes and this makes its usage advantageous for underwater concreting.

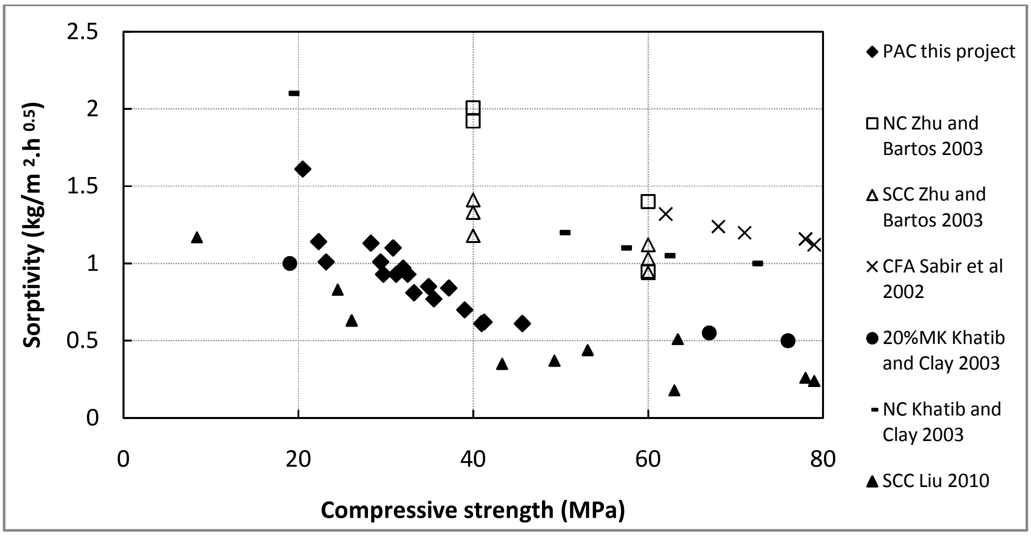


Figure 7.12 Sorptivity vs compressive strength for different types of concrete

7.7 Conclusions

The relations between different grouts and PAC properties were analyzed, and the relations between concrete properties were also correlated. Moreover, the effect of w/c ratio on the concrete-grout strength and sorptivity ratios were also presented. The following conclusions can be drawn

- PAC compressive strength decreases with an increase in water content using all types of sand and contents. On the other hand, concrete water sorptivity increase with the increase in water content using different sands and contents.
- At the same w/c ratio, the highest concrete compressive strength was produced by using S1 in grout and the lowest values were resulted from employing S2 showing a reflection of the effect of w/c on grout compressive strength. In contrast, S1 produced the lowest concrete sorptivity where the highest sorptivity resulted by using S2.
- PAC compressive strength and grout hardened strength are well correlated with coefficient of 0.86. The resulted relation can be used in the calculation of PAC compressive strength from grout compressive strength in the range of 36.15 –73 MPa when rounded coarse aggregate used.
- PAC sorptivity linearly increases with an increase in grout sorptivity with a correlation coefficient of 0.75. Although the correlation is not very strong due to the effect of coarse aggregate in concrete, it can be used in small scale testing on grout to predict PAC sorptivity.
- C/G compressive strength ratio increases with the increase in w/c ratio due to the higher relative effect on grout strength than concrete by increasing water content because of the greater amount of entrapped air in mortar at high w/c ratios. At the same w/c ratio, higher values of C/G compressive strength ratios obtained by using c/s of 1/0.6 than those of c/s of 1/0.9 due to the high cement paste content in grout which enough to cover all sand particles and improve the bond between the grout and the coarse aggregate.

- C/G sorptivity ratio decreases with the increase in w/c ratio due to the direct increase in grout voids by increasing water content. The relative low concrete sorptivity values compared with that of grout at high water contents is attributed to the effect of coarse aggregate which decreases the rate of concrete sorptivity at constant decrease rate in grout sorptivity
- Concrete compressive strength decreases with an increase in concrete sorptivity. Linear relationship was found between concrete compressive strength and sorptivity using all grouts regardless of sand type and content with coefficient of correlation of 0.76. However compressive strength is a function of porosity and sorptivity is a function of pore size distribution inside the concrete; these pores are part of volume of voids which affects on concrete compressive strength. This comparison can only be considered as a first estimation.
- Comparisons between sorptivity-compressive strength relations for PAC, normal concrete and self compacting concrete confirm that the lowest sorptivity was achieved by PAC at the same compressive strength. Consequently, a better durability is expected from the employment of PAC for underwater structures.

CHAPTER 8: CONCLUSTIONS AND RECOMMENDATIONS FOR FUTURE WORK

8.1 Introduction

In this study, the rheological behavior of paste and grout has been investigated using the Viskomat NT rotational viscometer. Moreover, grout consistency was also measured by the flow cone and modified flow meter tests; grout water bleeding was also measured. Portland cement (CEM1), grade 42.5 N was used in the production of cement paste and grout. Four different types of sand gradations were used in grout preparation at different w/c ratios of 0.35, 0.40, 0.45, 0.50, 0.55 and 0.60, at c/s ratios of 1/0.9 and 1/0.6 by volume.

Grouts were prepared first without any chemical or mineral additives then, SP was employed at 1% and 2% and finally grouts were made by replacing 20% of the cement weight by Pfa at 1% SP. Grout inject-ability through the coarse aggregate mass was investigated where the fresh grout rheology or consistency threshold was identified. After that, according to inject ability and less water bleeding, grouts of 1% SP and 20% Pfa were chosen to produce PAC. An 18 grout mixes were chosen to produce PAC, three different sands were used at three different w/c ratios and two different c/s ratios. Hardened grout flexure and compressive strengths and water sorptivity were then investigated. PAC compressive strength and water sorptivity also studied and a correlation between grout and concrete properties was developed taking into account sand type and content.

Detailed conclusions have been presented at the end of chapters 3 to 7. The most important of these conclusions are summerised below.

8.2 Conclusions

The main findings of this study are included as the following:

1. Effect of sand on grout rheology

- Effect of sand properties on grout rheology is controlled by the thickness of paste between aggregate particles. The distance between sand particles in grout is affected by the aerated sand voidage; the higher sand voidage consumes more paste and results in lower excess paste which consequently gives lower grout flow. The internal distance between sand particles can be calculated by dividing the excess paste volume by the surface area of sand.
- Grout rheology is affected by its cement paste rheology and sand properties. The effect of different sand properties can be expressed by the excess paste thickness between sand particles. For example, finer sand with higher voidage usually provides grout with higher yield stress and viscosity because of the lower distance between sand particles. Sand content also affects on grout rheology where the increase sand content at a given paste volume results in lower excess and consequently higher yield stress and viscosity.
- Grout-paste rheological properties increase with the decrease in the excess paste thickness to very low values until the sand surface roughness becomes important due to the high friction of sand particles. Consequently, sand surface texture can be considered as an important property especially at very low excess paste thickness in grout.

2. Superplasticizer dosage and water bleed

For PAC production, grout of high flow without water bleeding is essential, concluding that there is a necessity to avoid employing high water contents as much as possible, and that led to the use of the super-plasticizer at low w/c ratios. The dosages of SP was adjusted from 2% to 1% because of grout segregation resulted at 2% in some grouts. And also slightly less SP required for Pfa binary mixes than 100% Portland cement mixes. Grouts of 20% Pfa and 1% SP resulted in high flow at very low bleeding which is appropriate for the production of PAC.

3. Yield stress and plastic viscosity parameters

The work on grout mixes showed that yield stress and plastic viscosity are affected in different ways by different factors as explained below.

- Higher superplasticizer dosage resulted in a smaller change in both yield stress and plastic viscosity.
- Grout rheology decreases with the increase in w/c ratio.
- Sand type and content affected on the rheology as previously explained in section 1.
- Slight improvement of plastic viscosity by replacing 20% of cement weight with Pfa for 1% SP grouts was achieved.

4. Rheology tests

- Grout yield stress results show a threshold in the range of about (6-7) Nmm in the injection process through the coarse aggregate for all mixes. Moreover, the same threshold was recorded despite the difference in ingredients and materials added. As a result, yield stress property can be considered as an indication of grout injection in the design of PAC.

- In addition to the grout rheology tests, flow cone and modified Colcrete flow meter tests can be used to measure medium and high workability grouts. They are very useful in the field work where the rheology testing devices are not applicable.

5. Relationships between grout properties

- There are strong relationships between plastic viscosity and flow time, and plastic viscosity and speed of grout. Consequently, grout plastic viscosity parameter can be predicted from its flow time and its speed. Moreover, the modified flow meter test shows higher sensitivity than the flow funnel test especially for high plastic viscosity grouts.
- Good correlation was found between hardened grout flexure and compressive strengths, and compressive strength and sorptivity using different sands; the resulted relationships can be used in the prediction of any one from the other in the tested range regardless sand type and content.

6. Properties of hardened grout and PAC

- Factors affecting hardened grout and concrete can be expressed mainly by the quantity of water employed in the mix. Increasing w/c ratio in grout decreases the strength of both grout and concrete and increases their sorptivity. Other factors such as sand type and content can be related to the strength indirectly, to the quantity of paste required which of course linked also to the quantity of water.

7. Relationships between grout and PAC properties

- There are good relationships between hardened grout and concrete properties. Correlation between grout and concrete for compressive strengths was stronger than that of sorptivity tests, and that is attributed to the direct effect of coarse aggregate with high quantity in minimizing water transmission inside PAC. The transition zone between grout and coarse aggregate also is another player which affects on the correlation between grout and concrete of similar test methods.

8.3 Recommendations for future work

The following topics are recommended for future work:

- The effect of sand properties on grout rheology was investigated, for example void ratio and surface area, but there is a need to calculate the volume of pits and cavities within the sand particles by appropriate equipments to consider this volume in calculating the excess paste thickness. In addition, the appropriate technique will calculate the sand surface area accurately especially for very fine particle sizes.
- Although the limitation of channel length in the Colcrete flow meter was overcome by measuring the time required for the grout to reach certain distance and good correlation was found with the plastic viscosity, the sensitivity of the test for very low flow grouts is weak as it takes longer time to reach certain distance. Consequently, further investigation is beneficial to draw the border of the lower limit at which the test is not sensitive enough.

- Injection pressure of grout through the coarse aggregate was achieved by grout self weight gravity action. However the pressure was enough for high flow grouts and no pumps were used as that would disturb the upper layers of aggregate and loosens the advantage of contact points by separating aggregate particles by grout, the other reason was the small size of concrete casted. It is suggested to investigate the effect of the pressure on PAC production in large scale concretes to higher levels.
- A computational module is useful to imitate the flow pattern of grout inside the coarse aggregate mass in the production of PAC and that will help in designing of grout and PAC at low time and cost by minimizing the lab work.
- The relationships between grout and PAC for similar tests show that compressive strength correlation is higher than that of sorptivity due to the very low absorption of coarse aggregate. A wide range of coarse aggregates with different porosity is needed to investigate the limitation of coarse aggregate used in the production of PAC, and that is very important in the production of PAC for marine structures where concrete durability is critical.
- Work on grouts of SP for injection purposes showed self leveling behavior of grout opening the door widely for the possibility of producing PAC by injecting self compacting concrete (SCC) through the coarse aggregate particles in large concrete members where large particles of coarse aggregate can be used. This will minimize the whole cost of concreting as no pumps and compaction needed to achieve the work especially for underwater structures.

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Appendix A

Workability of mortar for preliminary study

Mortars were produced by using two different sands at three cement-sand ratios of 1/0.6, 1/0.9 and 1/1.2 by volume at water-cement ratios of 0.6, 0.55, 0.50, 0.45 and 0.40. Fresh mortar workability then measured by the flow meter and flow cone tests, their bleeding was also measured and the test results are shown below.

Mortars of Scrooby Top Sand (S1):

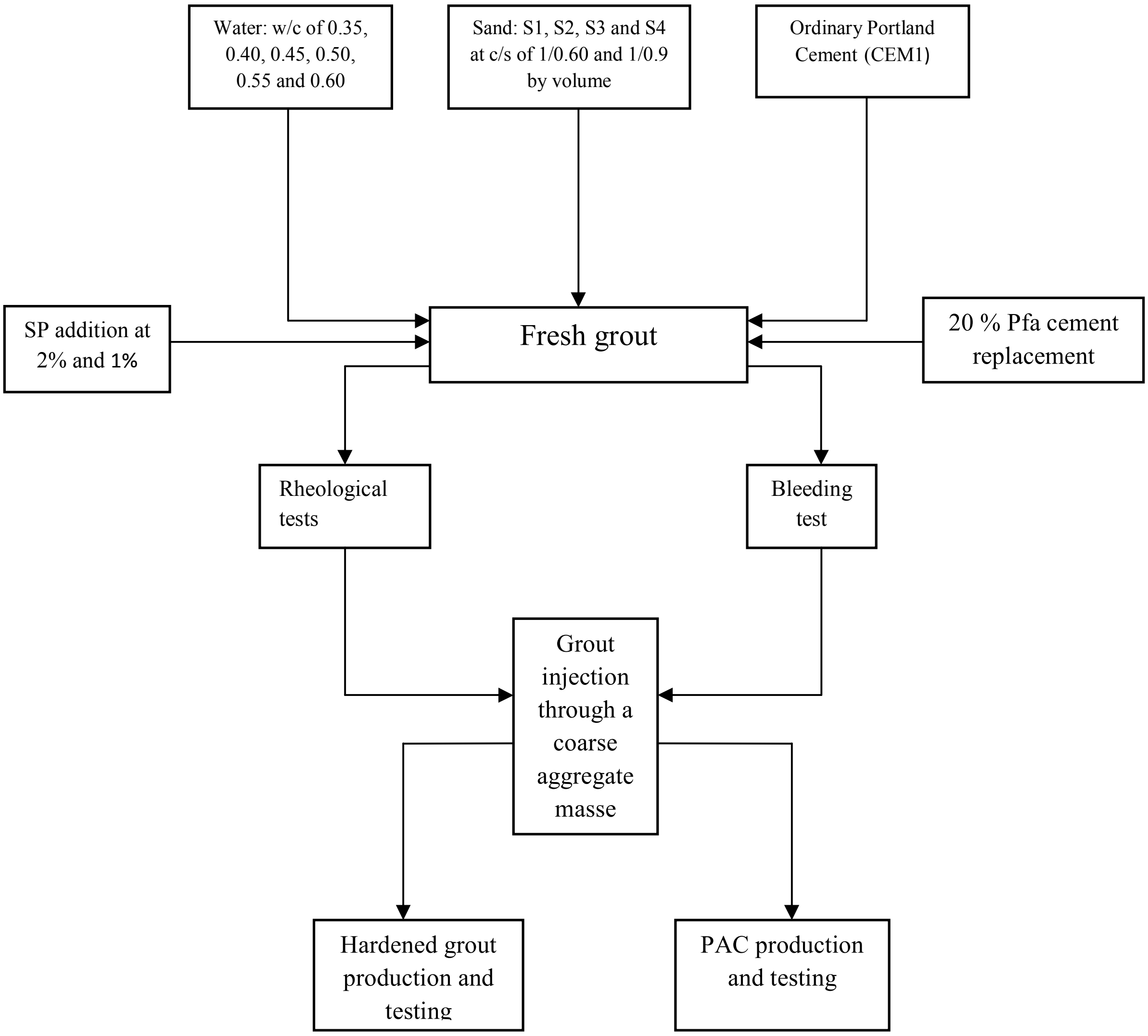
Mortar mix	c/s ratio	w/c ratio	Flow (cm)	Time (sec)	Bleed. (%)
G1-1	1/0.6	0.4	0	no flow	0
G1-2	1/0.6	0.45	19	no flow	0
G1-3	1/0.6	0.5	20	no flow	0.6
G1-4	1/0.6	0.55	35.5	no flow	2
G1-5	1/0.6	0.6	46.5	17	2.5
G2-1	1/0.9	0.4	0	no flow	0
G2-2	1/0.9	0.45	0	no flow	0
G2-3	1/0.9	0.5	1	no flow	0.4
G2-4	1/0.9	0.55	19	no flow	0.6
G2-5	1/0.9	0.6	32.5	60	0.8
G3-1	1/1.2	0.4	0	no flow	0
G3-2	1/1.2	0.45	0	no flow	0
G3-3	1/1.2	0.5	0	no flow	0
G3-4	1/1.2	0.55	0	no flow	0
G3-5	1/1.2	0.6	2	no flow	0

Mortars of Allerton Park Sand (S2) *:*

Mortar mix	c/s ratio	w/c ratio	Flow (cm)	Time (sec)	Bleed. (%)
G4-1	1/0.6	0.4	22.5	no flow	0
G4-2	1/0.6	0.45	37	32.5	0
G4-3	1/0.6	0.5	48.5	15	0
G4-4	1/0.6	0.55	58.5	12	2.1
G4-5	1/0.6	0.6	69	12	2.5
G5-1	1/0.9	0.4	1	no flow	0
G5-2	1/0.9	0.45	28	60	0
G5-3	1/0.9	0.5	31.5	38	0
G5-4	1/0.9	0.55	38	25.5	1.12
G5-5	1/0.9	0.6	58.5	14	1.8
G6-1	1/1.2	0.4	0	no flow	0
G6-2	1/1.2	0.45	9.5	no flow	0
G6-3	1/1.2	0.5	24.5	no flow	0
G6-4	1/1.2	0.55	36.5	25	0.6
G6-5	1/1.2	0.6	46	9	1.25

Appendix B

Experimental programme



Appendix C

Preplaced aggregate concrete cross section

At 28 days PAC cubic sample was cut into two pieces in order to insure that grout was penetrated all the coarse aggregate voids. It was found that the grout penetrated all the coarse aggregate voids without any honeycombing and the concrete is homogeneous as shown in the image below.