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Contents **المحتويات**

Research Papers in English

1- Influence of Fine Aggregate Type and Content on the Properties of Grout For Two-Stage Concrete
Manal F. Najjar, Enas A. Elmusrati, Amal M. El-khoja, and Abdurrahman A. Elgalhud 1

2- Influence of Polypropylene Fiber on Plastic Shrinkage Cracks of Concrete
Ashraf Abdalkader and Omer Elzaroug 13

3- Production of Siloxane Oils from Octamethylcyclo-Tetrasiloxane Using Equilibrium Ring Opining Reaction
Abduelmaged Abduallah, Omar Algeidi, Omar Sultan, Mohamed A. Ibrahim 25

4- The Effect of the Submerged Arc Welding Variables on Bead Geometry of Mild Steel Using Regression Analysis Technique
Abdulbaset A. Frefer and Al-Sonosi M. Abohusina 35

5- Simulation of Si Engine Performance and NOx Emissions
Abdorouf M. Naas, Fatima M. Ellafi, and Salem A. Farhat 51

6- Thermoeconomic Analysis of Alkhoms Steam Power Plant at Different Operating Loads
Haitham M. Elhejaji and Giuma M. Fellah 71

الأوراق البحثية باللغة العربية

1- دراسة عامة حول استخدام القوالب النسيجية في صب الخرسانة
حكيم عبد القادر السموعي وعلي سعيد البادن وهاجر محمد أبوصلاح 1

2- الاحمال المحورية وضغط الاطار لمركبات النقل بالطريق الساحلي قطاع (طرابلس – مصراته)
محمد الشتيوي بن عمر وعبد الحكيم علي الشماح 16

INFLUENCE OF FINE AGGREGATE TYPE AND CONTENT ON THE PROPERTIES OF GROUT FOR TWO-STAGE CONCRETE

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الملخص

تتميز الخـرسانة ذات المرحلتين بتقنية صب فريدة من نوعها، تتمثل في وضع الركـام أولاً في الشدات ثم حقنه بمونة ذات خواص انسيابية خاصة. حيث تتحكم جودة المونة المُستخدمة بشكل كبير في خواص الخـرسانة ذات المرحلتين. تُقدم هذه الورقة دراســـة حـول تـأثير نوع وكمية الركام الناعم على خـــواص المونة المستخدمة في إنتـــاج الخرسـانة ذات المرحلتين. تمت مقارنة نـــوعين مختلفين من الركـــام النـــاعم (رمـل البحر الطبيعي وركام نـــاعم مجـروش) وذلك باستخدام نسـب مختلفة من الركـام النـاعم إلى الإسمـــنت (fa/c = 0.5, 1.0, 1.5) مع تثبيت نسـبة المـاء إلـى الإسمنت (w/c = 0.45). تشير النتائج إلى أن المونة التي أُستخدم فيها الرمل الطبيعي تعطي قابلية أعلى للتدفق ومقاومة أقل للنضح من المونة التي أُستخدم فيها الركام الناعم المجروش. كما تؤدي زيادة محتوى الركام الناعم في المونة إلى تقليل قابلية التدفق، تقليل معدل النضح، وزيادة مقاومة الضغط. وكانت المونة التي أُستخدم فيها من الركام النـاعم المجروش عند (fa/c =1.0) و0.8% من الإضافة الملدنة فائقة الاداء الأفضل لإنتاج الخرسانة ذات المرحلتين، حيث حققت هذه المونة قابيليه تدفق جيدة، مقاومة ممتازة للنضح، ومقاومة ضغط عالية.

ABSTRACT

Two-stage concrete (TSC) is characterized by its exceptional placement technique, whereby aggregates are first pre-placed in the formwork then injected with a flowable grout. The quality of TSC grout is a controlling factor of the mechanical strength and durability of TSC. Therefore, this study investigates the properties of grout mixtures incorporating two types of fine aggregate including natural sea sand and crushed fine aggregate. The grout mixtures proportions were prepared at a water-to-cement ratio (*w/c*) of 0.45. Three fine aggregate-to-cement ratios (*fa/c*) of 0.5, 1.0 and 1.5 were tested. Results indicate that grout mixtures made with natural sand exhibited higher flowability and lower bleeding resistance than those made with crushed fine aggregate. Moreover, increasing the fine aggregate content reduced the grout flowability, while it improved the bleeding resistance and compressive strength. It was concluded that grout mixture made with crushed fine aggregate, (*fa/c*) = 1.0, and 0.8% high-range water-reducing admixture (HRWRA) was the best for successful TSC grout since it exhibited acceptable flowability, excellent bleeding resistance and high compressive strength.

KEYWORDS: Grout; Fine Aggregate; Flowability; Bleeding; Compressive Strength.

INTRODUCTION

Two-Stage Concrete (TSC), also known worldwide under different terms such as Prepacked Concrete and Preplaced Aggregate Concrete, is considered as a special type of concrete that is produced using a unique procedure, which differs from that of conventional concrete [1,2]. In TSC, coarse aggregates are first preplaced in the formwork, and then injected with a flowable grout mixture. The special placement technique of TSC provides various technological and sustainability advantages. Preplacing the coarse aggregate in the formwork before injecting grout permits using aggregate that constitute challenges in conventional concrete production. For example, very heavy aggregates (e.g. magnetite) can be used in TSC production without segregation concerns [1]. Moreover, recycled concrete aggregates that normally cause loss of workability and severe pumping problems will not contribute to concrete casting problems in the TSC technology [3]. Likewise, the TSC technique provides cost benefits since coarse aggregate, which is about 60% of the used materials, is directly placed into formwork and only the ingredients used to produce grout, which are about 40% of the total materials, go through mixing and pumping procedures. As a result, this will accelerate construction by reducing the volume of the concrete mixture and reduce the energy consumed in concrete mixing and pumping [1-2, 4-5].

Properties of the TSC grout and its ability to flow around the preplaced aggregate particles and fill voids have a dominant effect on the mechanical properties and durability of TSC [6]. The grout used in TSC normally consists of Portland cement, well graded fine aggregate, water, and chemical admixtures. The mixture proportions of TSC grouts are generally selected according to ASTM C938 [7], which mainly depend on the grout flowability. Previous research has concluded that grout with a time of efflux between 20 and 24 sec. is ideal for TSC [1, 8]. However, grout with time of efflux as high as 35 to 40 ± 2 sec is recommended for high-strength concrete [1]. In addition, the compressive strength of TSC depends on the ability of the grout to resist bleeding. In TSC, bleeding generally occurs at the underside of coarse aggregates, leading to formation of voids, which weak aggregate-grout interfacial zones, thus hindering the grout bond to coarse aggregates [2, 9]. Therefore, it is recommended that the bleeding of the TSC grout should be less than 0.5% [1].

The grading of the fine aggregate and its properties play a significant role in controlling the flowability of the grout. The used fine aggregate should be hard, dense, and stable [1, 2]. It was reported that using a well graded fine aggregate increased the stability of the grout and reduced segregation [10]. On the other hand, using fine aggregate with a high fineness modulus will increase the water demand, leading to a reduction in compressive strength and an increase of drying shrinkage. It was recommended that the fineness modulus of the used fine aggregate should range from 1.2 to 2.0 [2].

Moreover, the fine aggregate content has great influence on the flowability and stability of the grout mixture, thus TSC mechanical properties will be affected. It was reported that, at fine aggregate to cement ratio (*fa/c*) = 1.5 and water to cement ratio (*w/c*) = 0.4, the grout mixture was too thick to penetrate all voids between aggregate particles, leading to honeycombed TSC [4]. On the other hand, changing the (*fa/c*) ratio induced slight difference in TSC compressive strength [4]. It was concluded that at constant (*w/c*) ratio, the effect of different (*fa/c*) ratios on the TSC tensile strength was negligible [11], while reducing the (*fa/c*) ratio caused a reduction in modulus of elasticity [12-13].

However, there is currently scarce data that evaluate the influence of fine aggregate type on the flowability and stability of TSC grouts. Therefore, this study aims to investigate the effect of fine aggregate type on the properties of TSC grout. Two types of fine aggregates (natural sea sand and crushed fine aggregate), which are common used in Libyan market, were compared using different fine aggregate to cement ratios. Moreover, the effect of high-range water-reducing admixture (HRWRA) addition on the flowability of grout mixtures was monitored. The findings of this study should provide a database for TSC grout properties to pave the way for wider implementation of TSC in today's concrete industry, especially in Libya.

EXPERIMENTAL PROGRAM

Materials and Grout Mixture Proportions

Ordinary Portland cement was used for all tested grout mixtures. Table (1) summarizes the physical and mechanical properties of the used cement. Two types of fine aggregate were used. The first type was natural sea sand obtained from Zlietn quarry (nearly 200 km east of Tripoli city) with a specific gravity of 2.64 and absorption rate of 0.3%. The second type was crushed fine aggregate (Grinelya) with a specific gravity of 2.72 and absorption rate of 0.5%. Figure (1) shows the grading of two types of fine aggregate obtained from the sieve analysis. The grout mixtures proportions were prepared at a water-to-cement ratio (*w/c*) of 0.45, which was recommended to achieve the targeted flowability of grout for successful TSC production [6]. Three fine aggregate-to-cement ratios (*fa/c*) of 0.5, 1.0 and 1.5 were tested. A new generation, non-chlorinated, acrylic copolymer superplasticizer / high-range water-reducing admixture with a specific gravity of 1.06, and pH of 6 was added at different dosages in order to enhance the grout's flowability. The mixtures proportions of the tested grouts are provided in Table (2).

Table 1: The Physical and Mechanical Proprieties of Cement (OPC)

Test	Results
Cement consistency	30 %
Initial setting time	140 minutes
Final setting time	3.40 hours
Soundness	0.3 mm
Compressive strength of cement mortar at 3 days	25 MPa
Compressive strength of cement mortar at 28 days	46 MPa

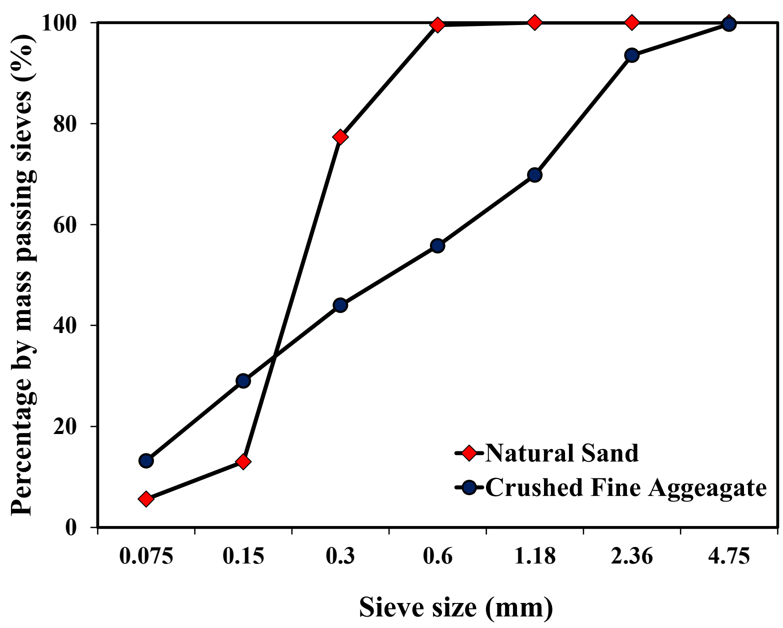

Figure 1: Grading curve of fine aggregate (natural sand and crushed fine aggregate)

Table 2: Grout Mixture Proportions

Grout Mixture ID	(*fa/c*) Ratio	Cement (kg/m^3)	Fine Aggregate (kg/m^3) Natural Sand	Fine Aggregate (kg/m^3) Crushed Fine Aggregate	Water (kg/m^3)
MN1	0.5	1043	521.5	-	469
MN2	1.0	871	871.0	-	392
MN3	1.5	748	1122	-	337
MC1	0.5	1048	-	524.0	472
MC2	1.0	879	-	879.0	396
MC3	1.5	756	-	1134.0	340

Experimental Procedures

All grout mixtures were prepared as per the guidelines of ASTM C938 [7]. Mixing and flowability measurements were conducted at room temperature (T = 23 ± 2°C). Immediately after mixing, the grout flowability was evaluated using a flow cone test according to ASTM C939 [8]. The flow cone test consists of measuring the time of efflux of 1725 ml of the grout through a specific cone having a 12.7 mm discharge tube.

In addition, the spread flow test was conducted to investigate the effect of HRWRA on the point where the grout mixture starts to spread freely [14]. The grout is filled in a special conical mould, which is lifted straight upwards in order to allow free flow. From the spread-flow test, two diameters perpendicular to each other (D_1 and D_2) are determined. Then, the relative slump, *Rp*, which is a measure for the deformability of the mixture, can be calculated using the following equation (1).

$$R_p = \left(\frac{\left(\frac{D_1 + D_2}{2}\right)}{D_o} \right)^2 - 1 \quad (1)$$

Where D_o represents the base diameter of the used cone (i.e. 100 mm).

Moreover, the resistance to bleeding of the grout mixtures was also evaluated according to ASTM C940 [15]. 800 ml of grout mixture is poured into glass graduated cylinder of 1000 ml volume. After three hours, the grout bleeding is calculated as per equation (2):

$$\text{Grout bleeding (\%)} = \frac{V_w}{V_1} \times 100 \quad (2)$$

Where V_1 is the volume of grout at the beginning of test (ml) and V_w is the volume decanted bleed water (ml).

The compressive strength of the TSC grout mixtures was monitored through testing 50 mm cubic specimens at the age of 28 days according to ASTM C942 [16]. Immediately after demolding, cube test specimens were moved to a curing tank until testing age.

RESULTS AND DISCUSSION

Flow Properties of TSC Grouts

Tables (3) and (4) report the efflux time and spread flow results for all the tested grout mixtures. At 0% HRWRA, it can be observed that all grout mixtures, which made with natural sand or crushed fine aggregate, showed very long efflux time or even did not show any measurable flowability. This can be attributed to that the water demand is lower than pore water volume that needed to fill up the voids between the solid particles. As a result, solid particles become connected by capillary forces. Thus, lubrication between particles is diminished and grouts will not flow under their own weight [17, 18].

Table 3: Grout Efflux Time Results

Grout Mixture ID	Grout Efflux Time (sec)		
	HRWRA Dosage		
	0.0 %	0.4 %	0.8 %
MN1	Long time*	21	11
MN2	Long time*	37	15
MN3	No Flow	Long time*	86
MC1	Long time*	33	19
MC2	No Flow	Long time*	47
MC3	No Flow	No Flow	No Flow

**Long time; Grout efflux time > 300 sec*

Table 4: Grout Spread Flow Results

Grout Mixture ID	Grout Spread Flow (mm)		
	HRWRA Dosage		
	0.0 %	0.4 %	0.8 %
MN1	172	293	350
MN2	131	191	320
MN3	113	133	230
MC1	144	224	331
MC2	100	164	238
MC3	100	100	108

However, adding dosages of HRWRA into grout mixture enhanced the grout's flowability as illustrated in Tables (3) and (4). For instance, addition of 0.4 % HRWRA improved the flowability of MN1 and MC1 mixtures to 21 sec and 33 sec, respectively. In addition, grout mixtures (MN1 and MC1) made with addition of 0.4% HRWRA achieved about 70% and 56% higher spread flow, respectively, compared with those made without addition of HRWRA. Indeed, HRWRA prevents the cement-water agglomeration and the formation of flocs through the steric repulsion mechanism. Moreover, HRWRA has unique polyethylene oxide side chains, which move in water and steer the cement grains to disperse evenly into the grout, thereby increasing the flowability [19-20].

On the other hand, grout mixtures made with natural sand exhibited better flowability than those made with crushed fine aggregate. For example, at 0.4% of HRWRA, MN1 mixture exhibited 36% shorter efflux time compared with that of MC1 mixture. Moreover, the spread flow for MN1 mixture was higher than that of MC1 mixture by about 31% at the same dosage of HRWRA. In fact, the water demand of grout mixtures made with crushed fine aggregate is higher than that of grout mixtures made with natural sand. This can be due to the following reasons: First, the shape of the crushed fine aggregate is angular with rougher surfaces compared with natural fine aggregate, which are rounder with smoother surfaces [21-22]. Second, natural sand contains low content of organic contaminant and silt in comparison with crushed fine aggregate. This is confirmed through particle size distribution of the used fine aggregates. As shown in Figure (1), around 13% particles were passed through 75 μm sieve in the case of crushed aggregate, while it was only 6% in the case of natural aggregate. Third, the absorption rate of the crushed aggregate was higher than that of natural sand by two-thirds. Due to the above mentioned reasons, grout mixtures made with crushed fine aggregate displayed lower flowability than the corresponding grout mixtures with natural sand [21].

As shown in Table (4), the spread flow of the grout mixtures depends on the HRWRA dosage. Therefore, the effect of the HRWRA on the spread flow was analyzed graphically. All measured relative slump values (Rp) were plotted versus the respective HRWRA dosage and a linear relation was computed for each mixture through linear regression as per the following equation (3):

$$HRWRA\ (\%) = SH_p\, R_p + H_p \tag{3}$$

Where H_p is the intersection of this linear function with the ordinates axis at R_p = 0, which is considered as the minimum HRWRA dosage to disperse the solid particles [23], *SHp* is the deformation coefficient, which indicates the required HRWRA dosage to increase the unit dispersing effect. The H_p values for MN1 and MC2 mixtures were less than zero. This hints that all tested grout mixtures with a (*fa/c*) = 0.5 can initiate flow behavior without the need for HRWRA addition. However, using HRWRA is still needed to achieve the targeted flowability for effective TSC production. Moreover, the fine aggregate type has a significant effect on the grout spread flow. As shown in Figures (2) and (3), MC2 mixture required a higher HRWRA dosage to disperse the powder particles (H_p = 0.0457) than that of the MN2 mixture (H_p = 0.0414).

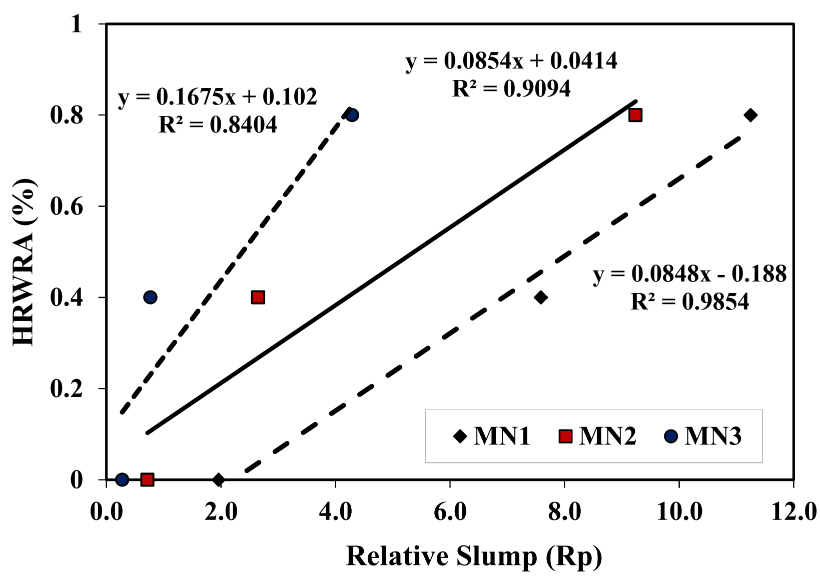

Figure 2: Relative slump flow based on the spread flow test as a function of HRWRA dosage for grout mixtures made with natural sand.

The fine aggregate content has a strong influence on the flowability of the grout. For example, at HRWRA= 0.8%, MN1 mixture (*fa/c* = 0.5) exhibited 87% shorter efflux time compared with that of MN3 mixture (*fa/c* = 1.5). In addition, at HRWRA= 0.4%, MC1 mixture (*fa/c* = 0.5) exhibited 124% higher spread compared with that of MC3 mixture (*fa/c* = 1.5). This can be attributed to that high fine aggregate content contributes to increase the plastic viscosity of grout mixture due to increase inter-particle friction [22]. Furthermore, increasing the fine aggregate content reduces the cementing action between aggregate particles, resulting in lower spread flow [22].

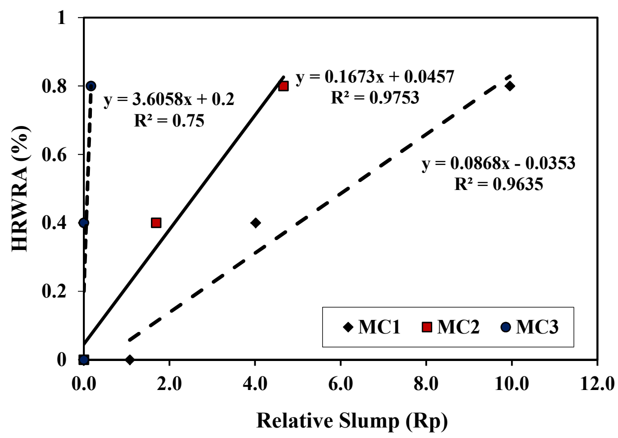

Figure 3: Relative slump flow based on the spread flow test as a function of HRWRA dosage for grout mixtures made with crushed fine aggregate.

Based on the flowability results discussed above, MN2 mixture made with addition of 0.4% HRWRA, MC1 mixture made with addition of 0.4% HRWRA and MC2 mixture made with addition of 0.8% HRWRA are considered as successful grout mixtures to produce TSC since these mixtures approximately meet the recommended efflux time according to ACI304.1 [1].

Grout Bleeding

Bleeding occurs due to the settlement of heavier solid particles suspended in free water under their own weight [24]. As shown in Figures (4-6), fine aggregate type has a significant effect on the grout bleeding. It can be observed that grout mixtures made with crushed fine aggregate achieved better stability than those made with natural sand. For example, at 0%, 0.4% and 0.8% HRWRA, MN2 mixture exhibited 44.4%, 37.5% and 150% higher bleeding, respectively, compared with MC2 mixture.

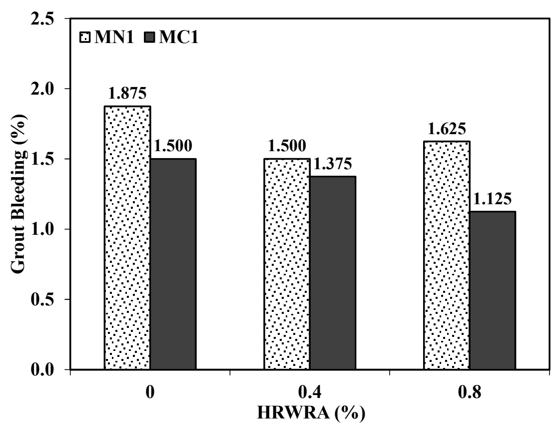

Figure 4: Influence of fine aggregate type on bleeding of TSC grouts conducted with different HRWRA dosages (*fa/c* = 0.5).

This can be ascribed to the high content of fines passing the 75µm sieve in case of crushed aggregate, leading to a reduction in the content of free water in the grout mixtures, thus reduction in bleeding [25]. Moreover, content of fine aggregate influences the stability (i.e. bleeding resistance) of grout mixtures. For instance, at 0% HRWRA, MC3 mixture exhibited 50% lower bleeding in comparison with MC1 mixture. This can be attributed to that increasing the amount of fine aggregate, which contains fine particles, can reduce bleeding due to absorption of free water [25].

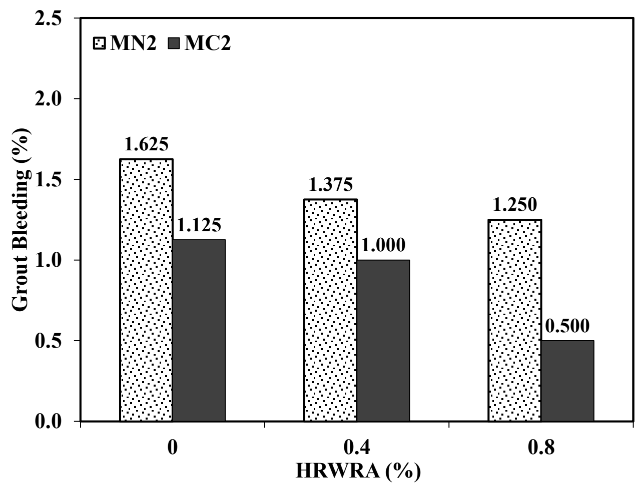

Figure 5: Influence of fine aggregate type on bleeding of TSC grouts conducted with different HRWRA dosages (*fa/c* = 1.0).

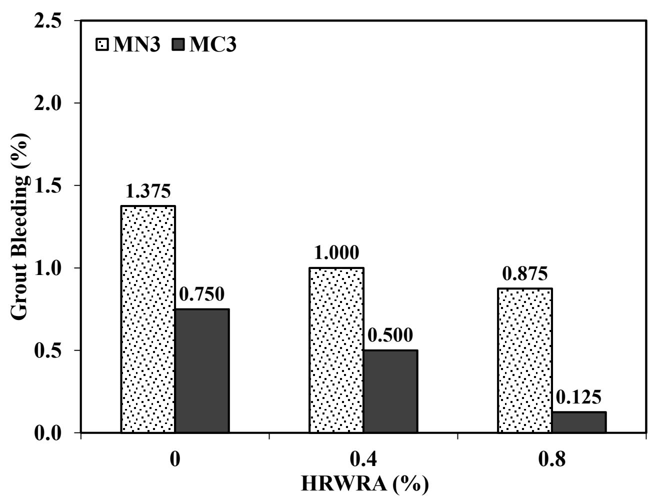

Figure 6: Influence of fine aggregate type on bleeding of TSC grouts conducted with different HRWRA dosages (*fa/c* = 1.5).

On the other hand, adding HRWRA has a great effect on grout bleeding. For example, increasing the HRWRA dosage from 0% to 0.8% reduced the bleeding of MC2 mixture by about 56%. This is due to the ability of the used admixture to enhance cohesiveness and stability of grout mixtures.

However, MN1 mixture made with 0.8% HRWRA showed an exceptional increase in the bleeding by about 8% compared with MN1 mixture made with 0.4% HRWRA. This can be attributed to the increase of free water in such mixture, leading to increase bleeding. This was emphasized by efflux time of MN1 mixture at 0.8% HRWRA, which was only 11 sec. According to the bleeding results discussed earlier, MC2 mixture made with the addition of 0.8% HRWRA was the best since it exhibited 0.5% bleeding with acceptable flowability for TSC.

Grout Compressive Strength

Figures (7-9) display the results of grout compressive strength. It was found that the compressive strength of grout mixtures made with crushed fine aggregate was higher than that of grout mixtures made with natural sand, especially at high fine aggregate content and high HRWRA dosage.

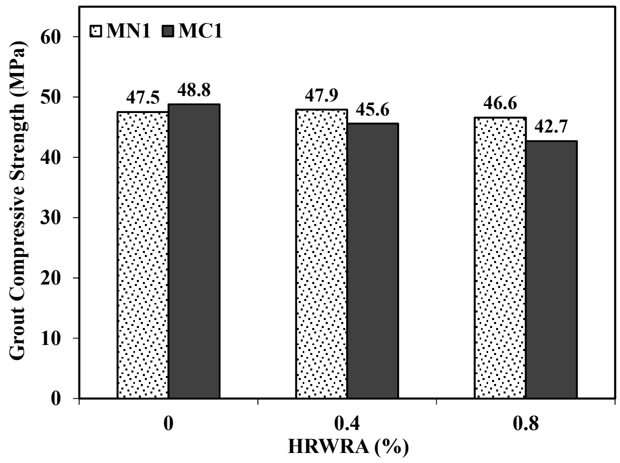

Figure 7: Influence of fine aggregate type on compressive strength of TSC grouts conducted with different HRWRA dosages (*fa/c* = 0.5).

For example, at 0.8% HRWRA, MC3 mixture exhibited 22% higher compressive strength in comparison with MN3 mixture. This can be attributed to that crushed aggregate has an angular shape which provides a higher surface-to-volume ratio, leading to better bond characteristics and strong interlock between particles [26]. On the other hand, natural sand exhibited lower compressive strength due to its rounded And smooth surface (i.e. less bonding characteristics) [26].

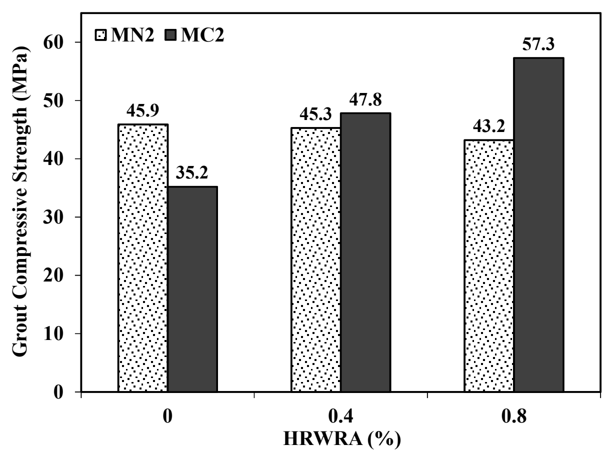

Figure 8: Influence of fine aggregate type on compressive strength of TSC grouts conducted with different HRWRA dosages (*fa/c* = 1.0).

Several studies concluded that increasing the content of fine aggregate showed an increase in grout (i.e. mortar) compressive strength [27]. Increasing fine aggregate content reduces the total porosity of cement mortar (i.e. grout) and the pores become finer with fine aggregate addition [27]. However, in this study, increasing natural sand content exhibited slight effect on grout compressive strength. For example, at 0.8% HRWRA, the compressive strength of MN1 and MN3 mixtures were 46.6 and 49.1MPa, respectively. Conversely, at 0.4% and 0.8% HRWRA, grout mixtures made of crushed aggregate showed improvement in compressive strength as the (*fa/c*) increased. For instance, the compressive strength of MC1 and MC3 mixtures were 42.7 and 60.0 MPa, respectively. This can be attributed to that the bond between binder and crushed fine aggregate are strong due to the high surface area and angular particles, resulting in higher compressive strength [26].

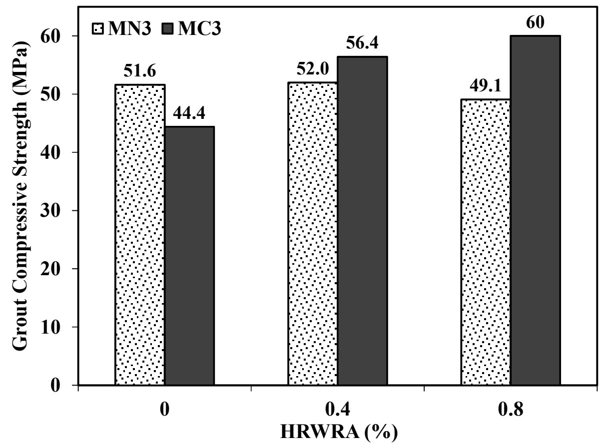

Figure 9: Influence of fine aggregate type on compressive strength of TSC grouts conducted with different HRWRA dosages (*fa/c* = 1.5).

However, MC2 and MC3 mixtures made without HRWRA resulted in low compressive strength compared with MC1. In fact, these mixtures produced voids, which are considered as a source of weakness in grout mixture as shown in Figure (10). These voids were formed since MC2 and MC3 mixtures, which made without addition of HRWRA, were too stiff and unworkable, leading to difficulties in the casting and preparing of the cubic specimens of grout.

Figure 10: Illustration of voids in MC3 mixtures made without addition of HRWRA

CONCLUSION

In this study, the flowability, bleeding and compressive strength of grout mixtures made with two types of fine aggregate (natural sea sand and crushed fine aggregate) were explored. The following conclusions can be drawn:

- Grout mixtures made with natural sand exhibited higher flowability and lower bleeding resistance than those made with crushed fine aggregate.
- Increasing fine aggregate content reduced the grout flowability, while it improved the bleeding resistance and compressive strength.
- At high fine aggregate content (i.e. *fa/c* = 1.0 and 1.5) and with addition of HRWRA dosage, the compressive strength of grout mixtures made with crushed fine aggregate was higher than that of grout mixtures made with natural sand.

- Grout mixtures made with *fa/c* = 0.5 and 1.0 can achieve the target flowability for TSC grouts specified in TSC standards, while those made with *fa/c* = 1.5 were too thick to use in TSC production despite the use of HRWRA admixtures.
- Grout mixture made with crushed fine aggregate, *fa/c* = 1.0 and 0.8% HRWRA was the best for successful TSC grout since it exhibited acceptable flowability, excellent bleeding resistance and high compressive strength.

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