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Effect of sand, fly ash, and coarse aggregate gradation on preplaced aggregate concrete studied through factorial design

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HIGHLIGHTS

- Effect of sand and fly ash in preplaced aggregate concrete (PAC) grout is studied.
- Fly ash can increase workability of PAC grouts.
- Sand in PAC mixtures increases mechanical strength of PAC.
- Effect of coarse aggregate gradation on PAC is studied.
- Coarse aggregate gradation does not affect mechanical strength of PAC.

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ABSTRACT

In casting preplaced aggregate concrete (PAC), coarse aggregates are preplaced into formworks then grouts are injected to fill voids. This casting method depends on the ability of the grout to fill voids, which depends on grout workability and coarse aggregate shape and gradation. The effects of fly ash replacement and sand content on low W/B (0.33) PA grout properties is studied, along with the effects of coarse aggregate gradation on PAC mixtures. Significant factor effects and interactions are identified through statistical factorial design of experiment. Results show that inclusion of sand reduces fresh grout workability while fly ash replacement in binders compensates for the loss of workability. The increase in sand content increases mechanical strength of PAC, while coarse aggregate gradation has no significant effect in PAC mechanical strength. Optimized sand and fly ash proportions improve strength up to 43%, 49% and 90% of compressive, tensile and flexural strength respectively, compared to pure cement PAC mixtures.

1. Introduction

Preplaced aggregate concrete (PAC) is cast by preplacing coarse aggregates into formworks after which grouts are injected to fill coarse aggregate voids. This method of casting is of great advantage to structural works where difficult placement conditions and limited site access are encountered [1]. As a relatively old concreting technique, PAC has been used in projects as early as 1938 for the rehabilitation of a tunnel lining on the Santa Fe Railroad in California [2]. It has also been used for restoration and strengthening of railway bridges and dams [3]. Surprisingly, only limited or vague information on PAC is found in literature, especially on the performance of sand extended grouts commonly used in PAC. Strength and performance data of PAC under different mixture combinations are also lacking [4,5]. An excellent overview of PAC, also known as two-stage concrete, is made by Najjar et al. in 2014 [5] where the authors also noticed the lack of experimental data on the performance of grouts under different binder combinations.

As part of a wider research to introduce the use of PA concrete in tropical climates such as Southeast Asia, this study aims to understand the performance and viability of preplaced aggregate concrete in a warm and humid climate using common concrete making materials in the region. The initial objective of this research is to develop an optimum grout for several PAC strength requirements using locally available materials and provide practical data on grout constituent effects on fresh and hardened mechanical properties.

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In PAC, the injected grout holds the coarse aggregates together. For this to occur, grouts should be able to fill all coarse aggregate voids. This depends on two main factors; grout workability and coarse aggregate void size. It is therefore fundamental to study the factors that affect these two main casting concerns and their effect on strengths of the final product. Beginning with the mixture optimization of PA grouts, the right combination of water, cement, pozzolans, and other additives that affect grout properties should be studied [6]. It has been shown that the use of a low-reactivity, finely grained material improves the necessary workability of cementitious materials [6]. In this study, a series of experiments is done to study the effects of sand and fly ash on grout mechanical properties such as workability and strength. Low water-to-binder (W/B) grouts are studied to ensure fresh grout stability, coarse aggregate interface bond and to maximize strength. Fly ash as a pozzolanic admixture is used to improve the fresh mechanical properties of low W/B grouts since it is known that fly ash improves fresh properties of mixtures [7], its use on injectable grouts are therefore advantageous, especially on low W/B grouts. Furthermore, Fly ash is abundant, cheap and commonly used for concrete making in the region. Sand is used as a particle filler to improve packing density of grouts, increase shear interlocking between particles, and reduce cost of the mixture. Chemical admixtures such as superplasticizers have also been used on PA concrete to improve grout flow and reduce water demand for mixtures [4], but its effects, proper dosages and reactions with other pozzolanic admixtures should be evaluated before actual field use [8]. All grout mixture combinations are initially screened for bleeding, pumping and filling performance to determine a suitable W/B ratio and superplasticizer dosage. Through this, sand and fly ash effect on the mixtures could be isolated thereby assuring useable fresh grout properties for all mixture combinations in the design space. To test the actual filling ability of these grouts for PAC use, coarse aggregate voids sizes are varied by changing coarse aggregate gradations. These specimens also allow the identification of the effects on strength properties of PA concrete with different coarse aggregate gradations.

2. Experimental program

The effect of sand, fly ash and coarse aggregate gradation on preplaced aggregate concrete (PAC) is studied by using statistical design of experiment (DOE) to efficiently isolate factors that affect mixture properties. Fresh grout properties such as, flow diameter, flow time, bleeding and setting time is measured. Grout compressive strength, PAC compressive strength, splitting tensile strength and flexural strength of specimens are determined after 90 days of curing, the first 7 days cured in water and the rest in a laboratory curing room (30 °C, 50% RH).

2.1. Design of experiment

A two-level factorial design 2^k with center points is selected for the analysis, with superscript k as the factor studied and 2 as the levels of each factors employed [9]. To distribute extraneous error effects, specimen preparation is done in a random order [10]. Center-points are replicated three times to check for non-linearity of responses and to estimate experimental error. Data points analyzed are the average of three readings or specimens. Since responses varied in a non-linear manner with the experimental factors, experimental points are added to model curvature and capture optimum mixture combinations. With this, a face-centered (alpha = 1) central composite design is formed. This method, a form of response surface design, makes it possible to generate quadratic models with linear main effects, two factor interactions, and the square terms of all factors [11]. Minitab statistical software is used to analyze data and plot charts.

Factor levels are selected through previous experience and initial grout screening experiment. To ensure usability of all grout mix proportions in the experimental space, factor levels are selected to produce grouts that fill coarse aggregate voids without segregation and bleeding. Minimum factor levels are set to 0 (pure cement grout). Maximum factor levels for fly ash replacement (FA/B), sand to binder (S/B), superplasticizer dosage in percentage of binder (SP%), and water-to-binder (W/B) ratio is set through an initial screening experiment based on target grout fresh properties as shown in Table 1.

Table 1
PAC grout fresh properties target.

Test	Requirement	Reference
Flow cone/efflux time (ASTM C939)	<40 s	ACI 304.1
Mini-slump cone (EFNARC 2002)	24–26 cm	EFNARC 2002
Bleeding (ASTM C940)	<2% after 3 h	ASTM C937

2.2. Materials

Ordinary Portland Cement Type-1 (ASTM C150) and locally sourced fly ash with specific gravity of 2.46, conforming to ASTM C618 as Type-F was used as the binder throughout the experimental procedure. Chemical composition of the cement and fly ash are shown in Table 2.

Natural river sand graded to a fineness modulus of 2.41 with a specific gravity of 2.65 is used throughout the study. Locally sourced crushed limestone was used as coarse aggregate (CA). From a single lot, CA is sieved into 3 gradations and adjusted to provide similar void contents of 45% measured through ASTM C29 [12] guidelines by rodding procedure. For each gradation, the particle size distribution, gradation standards and fineness modulus [13] is shown in Table 3 and Fig. 1.

The superplasticizer used is a polycarboxylate based admixture with a specific gravity of 1.06 and 30% solid content, supplied in a transparent light brown liquid. All materials are stored in sealed plastic containers inside the laboratory with an ambient temperature of 30 ± 5 °C and 50 ± 5% relative humidity.

2.3. Mixture proportions

Fifteen unique mixtures of PAC with varying fly ash replacement, sand ratio, and coarse aggregate gradation are studied. Mixture proportion coded levels and actual material ratios (by weight) are shown in Table 4, designed as to the requirements of a statistical central composite design. Study range of factors selected include; sand to binder ratio (S/B) of 0–1, fly ash to binder ratio (FA/B) of 0–0.4 and coarse aggregate grading (CA#) 1, 2, and 3. Water to binder ratio (W/B) and super plasticizer dosage (SP%) to produce an acceptable grout for pumping and void penetrability without exceeding 2% bleeding are selected to be 0.33% and 0.5% by binder weight respectively. Table 4 shows the DOE coded levels as well as the actual mix proportions for 1 cubic meter of PAC. Actual material weights are calculated from the total volume of grout produced while maintaining FA/B and S/B weight ratios. For example, when mix number 8 from Table 4 is desired, mix code PF0.4S1A3, with P signifying PAC, then F signifying FA/B followed by its weight ratio of 0.4, S as S/B followed by 1 as its weight ratio then A as coarse aggregate followed by 3, corresponding to the coarse aggregate code. From the weight ratios and their individual specific gravities, actual weight of materials can be calculated by producing grouts which include; 4 parts fly ash (FA/B = 0.4), 6 parts cement (60% of total binder weight), 10 parts sand (S/B = 1, equal to binder weight) and 3.3 parts water (0.33 W/B). Assuming all units are in kilograms, and dividing by their specific gravities, this mixture proportion will yield 10.6 L of grout. These calculated material weights can then be multiplied by 42.45 (450 L of desired grout ÷ 10.6 L yield of assumed mix proportion) to produce 450 L of grout for injecting into the 1 cubic meter coarse aggregate skeleton with 45% voids to produce PAC.

2.4. Grout mixing, fresh properties determination and specimen sampling

Casting of PAC is done in two stages: grout mixing and grout injection into formworks with preplaced coarse aggregate. Grouts are prepared in 50 L batches, using the same procedure throughout the study. First, the dry materials are mixed in a pan type concrete mixer for 5 min. Measured water is then loaded into the grout mixer and agitation is started. Premixed dry materials from the concrete mixer are then loaded into the grout mixer; mixing continually until all dry particles are hydrated, approximately 3 min. Superplasticizer is then added to the mixture while mixing continuously for another 2 min. Afterwards, fresh properties and grout sampling is commenced. Grout consistency is checked by the flow-cone [14]

Table 2
Chemical compositions of cement and fly ash used.

Chemical composition (%)	OPC Type I (%)	Fly ash (%)
SiO_2	20.48	42.64
Al_2O_3	5.25	20.49
Fe_2O_3	3.82	11.48
CaO	65	14.27
MgO	0.95	2.62
K_2O	0.4	2.84
Na_2O	0.08	0.62
SO_3	1.9	2.22
LOI	1.89	0.63

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