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Prediction of the steel-concrete bond strength from the compressive strength of Portland cement and geopolymer concretes

Zohra Dahou [a,*], Arnaud Castel [b], Amin Noushini [b]

[a] Laboratory Mechanics of Structures – LMS, University Tahri Mohamed – Bechar, Department of Civil Engineering, BP n° 417, Bechar, Algeria
[b] Centre for Infrastructure Engineering and Safety, School of Civil and Environmental Engineering, The University of New South Wales, Sydney, Australia

HIGHLIGHTS

- Bond models using compressive strength, for different concretes, are proposed.
- For OPC concrete, especially at early age, FIB model is non-conservative.
- A linear bond model is more appropriate when compressive strengths less than 25 MPa.
- For best bond prediction of geopolymer concretes the FIB model should be calibrated.

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ABSTRACT

The oldest and simplest bond test, which is the standard concentric pull out test, is usually used as a comparative test for different concretes in order to assess the bond with deformed bars. In this paper, two types of concrete are considered: Ordinary Portland cement (OPC) concrete and a novel concrete technology, namely geopolymer concrete (GPC). Bond strength was investigated by conducting pull-out tests on ribbed bars with a nominal diameter of 10 mm and/or 12 mm. The specimens were tested at various ages ranging from 1 to 28 days. Compression tests were performed at all ages as well. The main objective of the extensive research program involving 260 pull-out tests was to develop empirical models correlating the steel-concrete bond strength to the mean compressive strength of concrete for both OPC and geopolymer concretes. The models developed are compared to the existing model adopted by FIP Committee.

1. Introduction

The bearing capacity and serviceability of reinforced concrete elements depend on the bond between concrete and reinforcing bars. Steel-to-concrete bond allows longitudinal forces to be transferred from the reinforcement to the surrounding concrete. Bond is commonly regarded as a uniform shear stress over the surface of the bar. It may be defined as rate of variation change in axial force along the bar divided by the nominal area of bar surface over which that change takes place. The investigations which have contributed to the knowledge of many aspects of bonding agree that the interaction between the concrete and a bar is composed of three separate components [1,2]: Chemical adhesion, Friction, Mechanical interlock.

For ribbed-bars, adhesion and friction are secondary to the mechanical interaction of the ribs with the surrounding concrete. With increasing bar force, the mechanical interaction dominates the transfer of force which is concentrated near the rib faces. Increased loading will lead to bond failure near the ribs in two ways: crushing of concrete adjacent to the contact area and transverse cracking that initiate at the ribs [3–6]. The extents of these cracks cause bond failure either by the splitting of the concrete cover or by the pull-out of the steel bar. A variety of factors and parameters influence the bond [2]. The concrete quality, generally referred to as the concrete compressive strength, is of major importance. This strength is determined by quantitative and qualitative factors such as type of binder, water-cement ratio, grade of cement, size of aggregate, quality of manufacturing, etc. The age of the concrete also directly affects its strength. According to [7], concrete age has a significant influence on bond strength during the first three days after casting. It should also be emphasized that the bond strength increases faster than the compressive and splitting strength at early ages.

Over the last two decades, geopolymer concretes have emerged as novel engineering materials with the potential to become a

* Corresponding author.
E-mail address: dzohra@gmail.com (Z. Dahou).

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substantial element in an environmentally sustainable construction and building products industry [8–13]. Geopolymer concrete is the result of the reaction of materials containing aluminosilicate with alkalis to produce an inorganic polymer binder. Industrial waste materials, such as fly ash and blast furnace slag, are commonly used as the source of aluminosilicate for the production of geopolymer concrete due to the low cost and wide availability of these materials. With efficient use of other industrial by-products, geopolymer binder can reduce embodied CO_2 by up to 80%, compared to OPC [8].

Geopolymer concretes, despite their vastly different chemical composition and reactions [14,15] exhibit many of the characteristics of traditional concretes. The mixing process, the workability of freshly mixed geopolymers, the mechanical characteristics of the hardened material appears to be similar to those of traditional OPC concretes. However, only few attempts to assess steel-geopolymer concrete bond are reported in the literature. Sarker [16] investigated on bond strength of low calcium fly ash based geopolymer concrete with deformed reinforcing steel bars using the beam-end test. The results showed that geopolymer concrete has higher bond strength than OPC concrete for the same test parameters. Results were confirmed by Castel and Foster using the pull-out test and the same type of low calcium fly ash geopolymer binder [17].

This paper aims to develop empirical models correlating the steel concrete bond strength to the mean compressive strength of concrete for both OPC and geopolymer concretes. An extensive experimental program involving 260 pull-out tests has been carried out using ribbed bars with 10 mm and 12 mm nominal diameters. Three OPC concrete and two geopolymer concretes were studied using the RILEM pull-out test [18]. For the geopolymer concretes, one low calcium fly ash geopolymer binder [17] and one Ground granulated blast furnace slag (GGBFS) geopolymer binder were used. The specimens were tested at various ages ranging from 1 to 28. The models developed were compared to the existing model adopted by FIP Committee [19].

2. Experimental program

2.1. Portland cement concrete mixtures

The concrete mixes are presented in Table 1. The three concrete used were labelled VC40a, VC40b and VC30. Water to cement ratio was from 0.435 to 0.6. Two ordinary Portland cement (OPC) were used: 52.5 R (High early strength) and 52.5 N (Normal purpose). The crushed and river bed rolled aggregates, characterised by their round shape and smooth surface, used are siliceous. The ratio of crushed gravel to rolled gravel ranged from 1 to 2.35, which was the main difference between the two 40 MPa grade concretes. Also, the water to cement ratio was significantly higher for concrete VC40b. 24 h after casting, all OPC concrete samples, including pull-out test and compressive test specimens, were removed from their moulds and stored in a controlled environment (T° = 23 °C, RH% = 65%) until the day of the test. The 28 days average compressive strength and elastic modulus of all OPC concretes are presented in Table 1.

Table 1
Mixes and 28 days mechanical properties of OPC concretes.

	VC40a	VC40b	VC30
Cement CEM I 52.5 R CE CP2 NF LAFARGE (kg/m^3)	425	375	–
Cement CEM I 52.5 N CE CP2 NF Calcia (kg/m^3)	–	–	325
Sand 0/4 kg/m^3	710	755	811
Rolled gravel 4/10 kg/m^3	532.5	336	382
Crushed gravel 10/14 kg/m^3	532.5	790	731
Total water (kg/m^3)	185	187.5	195
W/C (water-cement ratio)	0.435	0.5	0.6
G/S (Gravel-sand ratio)	1.5	1.5	1.37
Gc/Gr (Crushed-rolled gravel ratio)	1	2.35	1.91
Compressive strength (MPa)	43.9	43.8	36.8
Elastic modulus (GPa)	32.0	34.2	25.1

2.2. Geopolymer concrete mixtures and curing regime

Two geopolymer concrete mixes were used for this study. They were designed using the outcomes from both literature [20–26] and laboratory trials where different aluminosilicate materials proportions (fly ash and GGBFS), various activator concentration (8 M to 14 M) and activator to aluminosilicate source ratio (0.42–0.6) were tested.

Three different sources of aluminosilicate materials have been used in this study: A low-calcium type (ASTM C 618 Class F) fly ash (FA), sourced by Eraring Power Station in New South Wales, Australia; a special grade (ultra-fine) fly ash branded as Kaolite High Performance Ash (HPA) sourced by Callide Power Station in Queensland, Australia and a ground granulated blast furnace slag (GGBFS) supplied by Blue Circle Southern Cement Australia. All details related to those three aluminosilicate materials such as oxide compositions (Table 2) and grading curves (Fig. 1) are available in [17]. The alkaline solution was made from a mixture of 12 molar (M) sodium hydroxide (NaOH) solution and sodium silicate solution with Na_2O. The mass ratio of alkaline solution to aluminosilicate material was 0.55.

The two Geopolymer concrete mixes are presented in Table 3. The first geopolymer concrete mix (labelled GPC-FA) contains only 15% of GGBFS. It is a low calcium geopolymer concrete. The second geopolymer concrete mix (labelled GPC-S) contains 75% of GGBFS. It is a high calcium geopolymer concrete. All geopolymer concretes were compacted using a poker vibrator and demoulded 24 h after casting. The low calcium geopolymer concrete GPC-FA required an intense heat curing to achieve an acceptable performance. Two types of heat curing conditions were adopted:

- 2D-curing: After casting, specimens were sealed to prevent excessive loss of moisture, stored in 80 °C oven for 1 day and then cured in a 80 °C water bath for a further 1 day. Then, all specimens where transferred to a controlled room with 23 °C and 65% relative humidity until the day of the test.
- 7D-curing: After casting, specimens were sealed to prevent excessive loss of moisture, stored in a 40 °C oven for 1 day and then cured in a 80 °C water bath for a further 7 days. All specimens were then transferred to a controlled room with 23 °C and 65% relative humidity until the day of the test.

Table 2
Chemical compositions of FA, Kaolite HPA and GGBFS by x-ray fluorescence (XRF) analysis.

Oxide	FA [wt. %]	Kaolite HPA [wt. %]	GGBFS [wt. %]
Silicon dioxide, SiO_2	66.56	45.14	31.52
Aluminium oxide, Al_2O_3	22.47	33.32	12.22
Iron oxide, Fe_2O_3	3.54	11.99	1.14
Calcium oxide, CaO	1.64	4.13	44.53
Potassium oxide, K_2O	1.75	0.13	0.33
Sodium oxide, Na_2O	0.58	0.07	0.21
Magnesium oxide, MgO	0.65	1.37	4.62
Manganese oxide, MnO	0.06	0.23	0.36
Phosphorus oxide, P_2O_5	0.11	0.56	0.02
Titanium oxide, TiO_2	0.88	2.19	1.03
Sulphur trioxide, SO_3	0.10	0.48	3.24
Loss of ignition (LOI)	1.66	0.41	0.79
Specific gravity[a]	2.1	2.4	2.8
Appearance	Grey	Dark grey	Chalky white

[a] Tested in accordance with AS 1141.6.2 (1996), using the pycnometer method.