

A Comprehensive Experimental Study on the Performance of Fly Ash concrete

Asma Abd Elhameed Hussein, Nasir Shafiq, Muhd Fadhil Nuruddin

Abstract—In this study, the effect of fly ash on concrete workability, compressive strength, splitting tensile strength and bond strength was investigated. The ordinary Portland cement was replaced with 5 to 50% fly ash, it was observed that 10 % fly ash showed the highest compressive strength at all ages, use of 15%-30% fly ash significantly increased the compressive strength at 90 and 180 days. The fly ash improved the bond strength of concrete at all replacement levels. It was concluded that 10%FA and 15%FA were the optimum replacement levels for all the investigated properties.

Index Terms— Fly Ash, workability, Compressive Strength, Splitting Tensile Strength, Bond strength, Pull out test.

I. INTRODUCTION

Utilization of agricultural, industrial and agro- industrial by-products in the form of processed ash attracting researchers to explore their potential as cement replacement materials CRMs or mineral admixtures to the properties of concrete at multiple level. Utilization of established materials such as silica fume, fly ash and ground granulated blast furnace slag has proved as the high performance concrete ingredients. The benefits were mainly derived from presence of high SiO₂ content and amorphous mineralogical character, which caused high strength and stability of the end product [1],[2]. Since last few years tremendous efforts have been made to increase the use of cement replacement materials in concrete production because the cement production consumes high energy and is responsible for 5% of global anthropogenic CO₂ emission (each ton of cement produces about one ton of CO₂) and their use can also improve the properties of concrete [3].

Fly ash is the by-product obtained by electrostatic or mechanical precipitation from the exhaust gases of coal-fired power plants and it is the most commonly used pozzolan [4]. The effects of fly ash as CRM on concrete properties have been addressed by different researchers around the world and they concluded that inclusion of fly ash can improve the flow ability, mechanical properties as well as the durability of concrete [1], [5] – [11].

As in [5], type 1 Portland cement was replaced with 58% fly ash to investigate the effect of different curing conditions on the strength and durability of concrete. Four curing regimes, namely, moist curing, curing at room temperature, curing at room temperature after two days moist curing and curing at 38 °C and 65% relative humidity were examined.

Manuscript published on 30 August 2013.

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It was found that the highest compressive strengths can be achieved by continuous moist curing and it was also reported that, inclusion of high volume of fly ash led to reduction in permeability and the high resistance to chloride ion penetration. Bond strength of concrete is an important factor for structural design, the axial force transferred from the reinforcing bar to the surrounding concrete results in the development of tangential stress components along the contact surface. The stress that acting parallel to the bar along the interface is known as bond stress. the bond strength is a combination of chemical adhesion, friction and mechanical interlocking between the bar and the surrounding concrete for the deformed bars [12]. The bond strength was studied by different researchers for normal and light weight concrete and for different cement replacement materials such as silica fume was studied by [13], [14], effect of fly ash on bond performance was also studied by [15].

Structural properties of concrete containing fly ash including bond strength need to be investigated. The principal aim of this research paper is to present the results of an experimental study performed to investigate the effect of fly ash on the mechanical properties of concrete namely compressive strength, splitting tensile strength and bond characteristic of concrete.

II. MATERIALS

The ordinary Portland cement (OPC) type 1 was used in this study it was complying with the requirements of BS 12 (1996) [16] and MS 522 (1989) [17]. The chemical composition of cement is shown in Table 1. Crushed Granite rocks with a maximum particle size of 20mm was employed as coarse aggregate and mining sand with a maximum particle size of 4.75mm was used as fine aggregate according to BS 812-103.2 1989 [18]. A naphthalene formaldehyde sulphonate superplasticizer in the form of aqueous solution was used as water reducing admixture (WRA) for all concrete mixes.

A. Properties of Fly Ash

The fly ash used in this study was obtained from Manjung Power Station at Lumut, Perak, Malaysia. The chemical composition of fly ash was determined using X-Ray fluorescence technique (XRF), the chemical properties of fly ash are given in Table 1. The major oxide observed in fly ash is silica (SiO₂), which is about 56.39%, the total summation of SiO₂+ Al₂O₃+ Fe₂O₃ is 89.03%, the calcium oxide, CaO is 5.47%, hence this ash classifies as class F pozzolan according to ASTM C 618 2009 [19]. The X-Ray diffraction (XRD) analysis of the fly ash shows the amorphous silicon oxide and aluminum silicate as shown in Figure 1.



The image of the fly ash used in this study is shown in Figure 2. The morphology of the fly ash particles was determined with aid of Field Emission Scanning Electron Microscopy (FESEM) technique at magnification of 10000X, 5000X and 50X and are shown in Figures 3, 4 and 5 respectively. At 10KX and 5KX the spherical shape of fly ash is very evident, and the particle size was measured at 50X, more than 95% having a particle size of 20 micrometer and the rest have a particle size of 47-51µm.

TABLE 1 CHEMICAL COMPOSITION OF OPC AND FLY ASH

Oxide	Weight %	
	OPC	Fly Ash
SiO ₂	20.44	56.39
Al ₂ O ₃	2.84	23.57
Fe ₂ O ₃	4.64	9.07
CaO	67.73	5.47
K ₂ O	0.26	1.98
MgO	1.43	0.98
Na ₂ O	0.02	1.91
P ₂ O ₅	0.10	-
TiO ₂	0.17	-
MnO	0.16	-
SO ₃	2.20	0.55
SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃	-	89.03

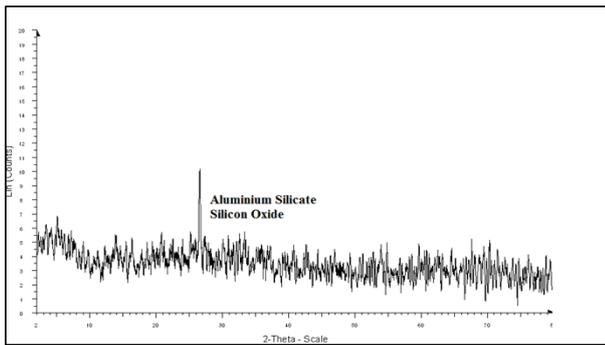


Figure 1 XRD Pattern of fly ash



Figure 2 Fly Ash

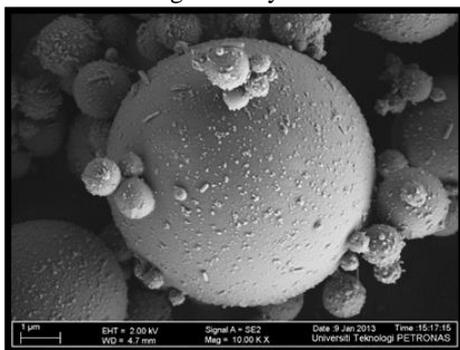


Figure 3 FESEM image of fly ash at 10KX magnification

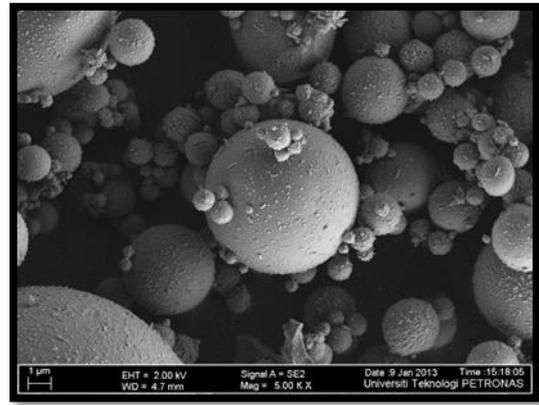


Figure 4 FESEM image of fly ash at 5KX magnification

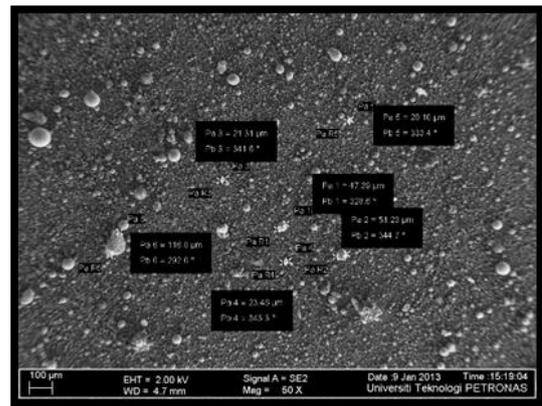


Figure 5 FESEM image of fly ash at 50X magnification

III. EXPERIMENTAL PROGRAM

A. Concrete Mixing and Casting

A total of 11 concrete mixes were prepared, one of the mixes was made of 100% ordinary Portland cement (no FA content), denoted by NC and called the reference mix. The remaining 10 mixes were prepared by adding fly ash content as partial replacement to cement i.e. 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45% and 50%; these mixes are denoted by Fly Ash content, e.g. 5%FA. Details of all mixes are given in Table 2. All concrete ingredients were mixed according to the procedure given in BS1881-125: 1986 [20], the superplasticizer dosage was kept constant as 0.6% by weight of cement.

B. Workability

The workability of the freshly mixed concrete was determined using slump test that was performed according to BS 1881: Part 102: 1983 [21].

TABLE 1 CONCRETE MIX PROPORTIONS

Mix Description	OPC	Fly Ash	CA	Sand	Water	SP
NC	500	0	945	745	190	3
5% FA	475	25	945	745	190	3



10% FA	450	50	945	745	190	3
15% FA	425	75	945	745	190	3
20% FA	400	100	945	745	190	3
25% FA	375	125	945	745	190	3
30% FA	350	150	945	745	190	3
35% FA	325	175	945	745	190	3
40% FA	300	200	945	745	190	3
45% FA	275	225	945	745	190	3
50% FA	250	250	945	745	190	3

C. Compressive Strength

The compressive strength was determined using 100 mm cubes at the age of 7, 28, 90 and 180 days curing. During compression test, the load on the cube was applied at a constant rate of 3.0 KN/s according to BS 1881: Part 111: 1983 [22].

D. Splitting Tensile Strength

The split cylinder test was done on 100 mm diameter and 200 mm length cylinder specimen and the tensile strength was at 28, and 90 days of curing. The concrete cylinder was placed between the platens of the testing machine in the horizontal axis. The load was applied until the cylinder specimen split into two halves. The test was conducted according to BS 1881: Part 117: 1983 [23].

E. Pull Out Test

The pull out test was conducted on a concrete cylinder 100 mm diameter and 200 mm height with a 12 mm diameter deformed steel bar of 652.4 MPa tensile strength embedded in concrete in order to determine the concrete-steel bond. The test was done in accordance with ASTM C 234-91a: 1999 [24] with aid of universal testing machine with a loading rate of 0.367 KN/s as shown in Figure 6. The measured bond strength was obtained from the following equation:

$$F_{bd} = \frac{P_{max}}{\pi \phi l_b} \quad (1)$$

The theoretical bond strength was calculated according to BS EN 1992-1-1 cited in [25] by using the following equation:

$$f_{bd} = 2.25 \eta_1 \eta_2 f_{ctd} \quad (2)$$

The theoretical bond strength was also calculated according to [12] by using the following equation:

$$u = \sqrt{f_c'} \left[2.28 - 0.208 \frac{e}{d_b} - 38.212 \frac{d_b}{l_d} \right] \quad (3)$$



Figure 6 Test Set up for Pull out Test

IV. RESULTS AND DISCUSSION

A. Effects of Fly Ash on Workability

Figure 7 shows the slump values for all the concrete mixes. Since the water content and superplasticizer dosage was constant in all mixes, therefore, the effect of fly ash on workability of concrete can be better understood. As shown in Figure 7, the workability of concrete was dramatically increased with the increment in the fly ash content. For reference concrete, NC the slump value was obtained as 160 mm, whereas for 50%, the slump was about 275 mm and the concrete was very similar to the self-compacting concrete. It means the increasing of fly ash content reduces the water demand in concrete for achieving a desired workability which is beneficial for the high performance concrete production. The improvement in the workability of concrete can be attributed to the fineness and spherical shape of fly ash particles. Similar observations were also reported in the available research by others [4], [26], [27].

B. Effect of Fly Ash on Compressive Strength

Figure 8 shows the compressive strength of all mixes determined at the age of 7, 28, 90 and 180 days. 5%FA marginally increased the compressive strength at 7 and 28 days and significantly improved the compressive strength at 90 and 180 days an improvement of about 19.6% and 20.6% over the control was obtained at 90 and 180 days respectively. 10%FA exhibited highest early age compressive strength among all the fly ash mixes with very excellent strength development at 28 days onward, an increase of about 14%, 27% and 28% was obtained at 28, 90 and 180 days respectively when compared to the normal concrete, Similar observation was reported by [6].

15%FA and 20%FA slightly altered the compressive strength at 7 and 28 days but significantly improved the 90 and 180-day compressive strengths, 25%FA showed slightly lower compressive strength compared to NC at 28 days but higher at 90 days and 180 days, the reduction in early age strength of fly ash concrete can be attributed to the slow pozzolanic reaction of fly ash. 40%FA, 45%FA and 50%FA significantly reduced the compressive strength at all ages but still there is a continuous development in the strength, the compressive strengths for mixes 40%FA, 45%FA and 50%FA were 64.74 MPa, 59.83 MPa and 55.91 MPa respectively which can be considered as medium strength concrete and can be used in ordinary construction works or mass concrete works. In general Up to 30% fly ash replacement the concrete had higher compressive strength than normal concrete at 90 and 180 days, at 35% and 40% replacement the compressive was slightly lower than normal concrete while a significant reduction in compressive strength was obtained at 40% and 50% fly ash replacement these results are in agreement with [8], [11], [28].

C. Effect of Fly Ash on Splitting Tensile Strength

The splitting tensile strength results at 28 and 90 days are shown in Figure 9. Effects of fly ash content on tensile strength follow similar trend that observed in compressive strength.

A Comprehensive Experimental Study on the Performance of Fly Ash Concrete

The mixes 10%FA showed highest tensile strength among all mixes, it showed 20% and 27% higher tensile strength than the reference mix NC at the age of 28 and 90 days respectively. Up to 25%FA replacement level the splitting tensile strength was found higher than that of the reference mix at 28 and 90 days. 30%FA showed the similar tensile strength as that of the reference mix at 90 days, whereas 35%FA-45%FA showed between 6-18% lower than the reference mix at 28 days and between 2-13% lower tensile strengths at 90 days, 50%FA reduced the 28 and 90-day tensile strength by about 24% and 32% respectively as compared to the control mix, NC. The reduction in the splitting tensile strength at high volume of fly ash can be attributed to inclusion of superplasticizer because the fly ash significantly improved the workability which means the

water content should be reduced in order to achieve high compressive and tensile strengths [27].

The ratio of the splitting tensile strength to the compressive strength at 28 days for all the mixes was calculated in the range of 6.8% to 7.9%, this ratio was decreased with the increase of compressive strength [29].

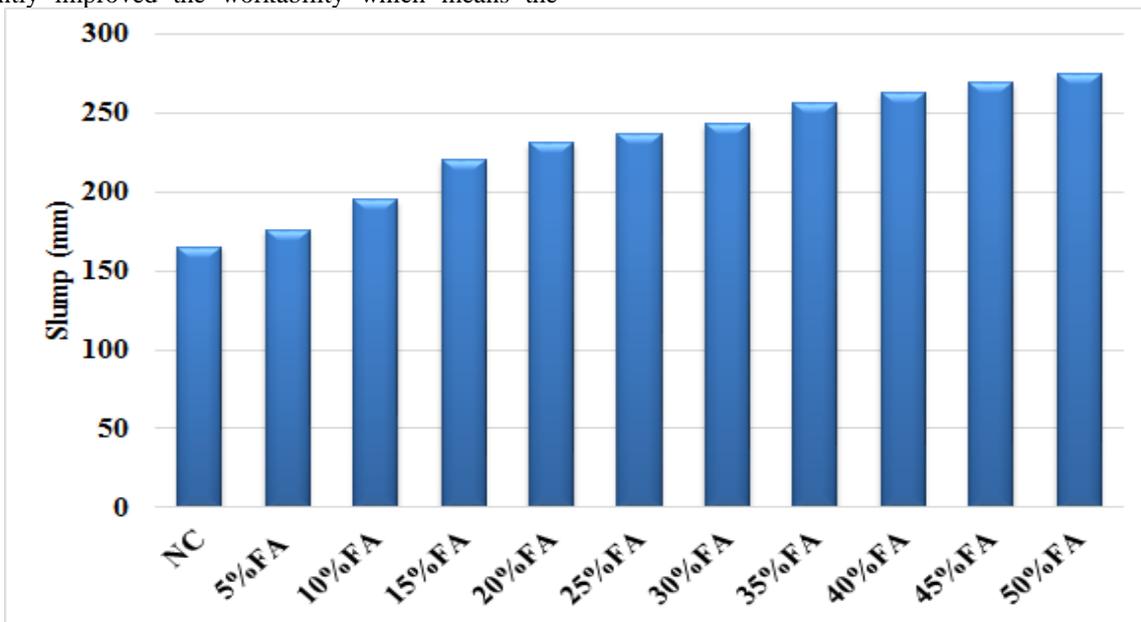


Figure 7 Effect of fly ash on the workability of concrete

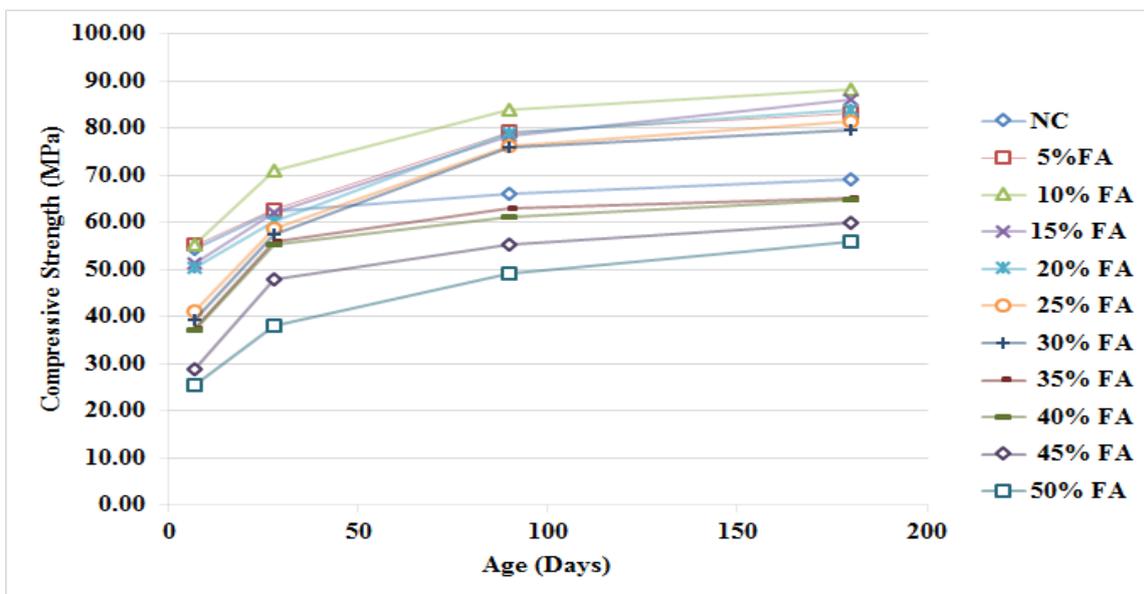


Figure 8 Effect of fly ash on the compressive strength of concrete

D.Effect of Fly Ash on Bond Strength

Figure 10 shows the load versus slip for all tested specimens, and Table 3 presents the results of failure load, measured bond strength and the calculated bond strength according to BS EN 1992-1-1 and according to a formula suggested by [12], the results showed that 5%FA improved the bond strength by about 9% over the control specimen and the sample failed due to the concrete splitting and rebar pull out, 10%FA and 15%FA had almost similar bond strengths 9.57 and 9.47 MPa respectively which was about 38% higher than the reference specimen, NC and they failed due to steel rupture, Steel rupture failure indicates that the bond between the steel bar and concrete is very high therefore the rupture occurred before the bond or the adhesion and interlocking between the bar and surrounding concrete fails which clarify that the actual bond strength for the specimens 10%FA and 15%FA has not been reached yet due to the steel rupture and these two specimens would have shown higher bond strength

if the steel bar had higher tensile strength. 20%FA-50%FA specimens failed in the similar manner as the control and 5%FA specimen by splitting of concrete and rebar pull out, the splitting failure usually occurs when the concrete between the reinforcing bar ribs (concrete keys) becomes weak [14], in other words the specimens 20%FA-50%FA reached their actual bond strength. The improvement in the bond strength for 20%FA-35%FA specimens were found to be in the range of 18-25% higher than the control specimen and the bond strength for specimens 40%FA-50%FA were 7-14% higher than the control specimen and the improvement was higher for lower replacement percentages .

The failure patterns are shown in Figure 11. The comparison of the measured bond strength obtained in this study and the theoretical bond strength calculated according to Euro code 2 and according to [12] is presented in Figure 12.

TABLE 1 PULL OUT TEST RESULTS

Specimen	P _{max}	Measured Bond Strength (MPa)	Calculated Bond Strength (MPa) according to BS EN 1992-1-1	Calculated Bond Strength (MPa) according to Hadi, 2008 [12]	Failure mode
NC	51.93	6.89	9.68	11.93	Splitting+pullout failure
5%FA	56.46	7.49	11.16	13.05	Splitting+pullout failure
10% FA	72.18	9.57	12.31	13.44	Steel ruputr failure
15% FA	71.42	9.47	11.99	12.98	Steel ruputr failure
20% FA	64.95	8.61	11.50	13.03	Splitting+pullout failure
25% FA	63.94	8.48	10.37	12.80	Splitting+pullout failure
30% FA	61.12	8.11	9.83	12.78	Splitting+pullout failure
35% FA	61.34	8.13	9.47	11.62	Splitting+pullout failure
40% FA	59.07	7.83	9.09	11.47	Splitting+pullout failure
45% FA	55.83	7.40	8.39	10.90	Splitting+pullout failure
50% FA	55.63	7.38	7.38	10.28	Splitting+pullout failure

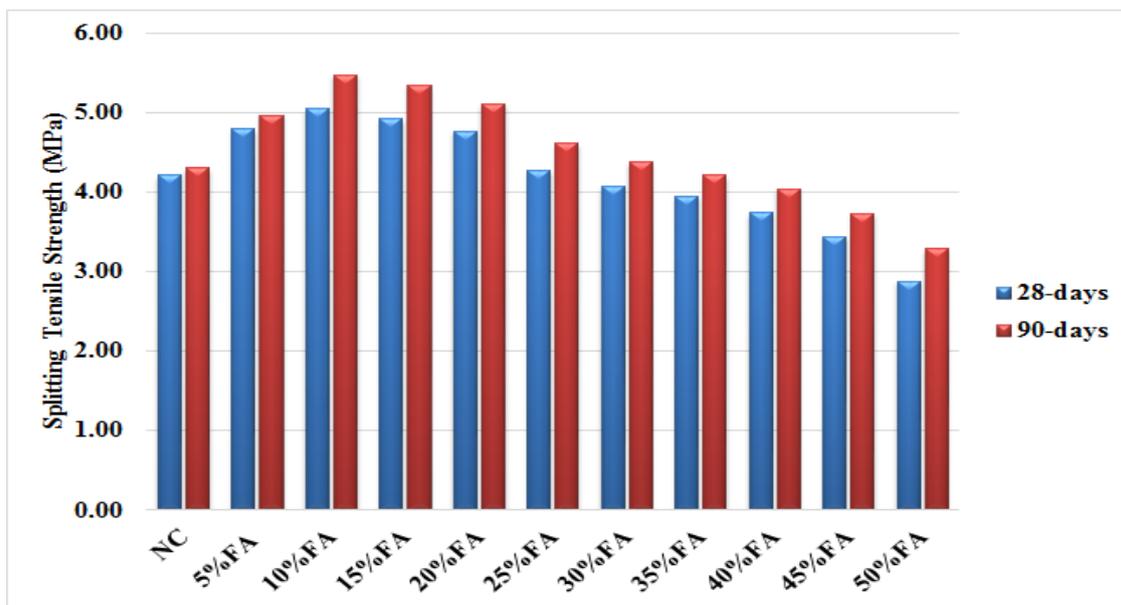


Figure 9 Effect of fly ash on splitting tensile strength of concrete

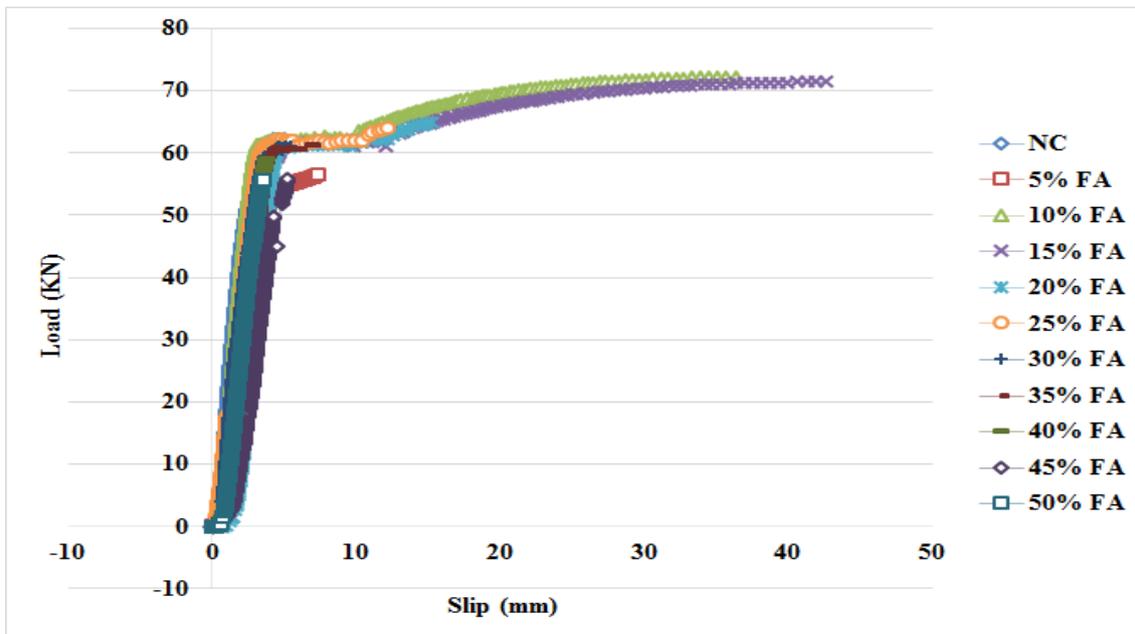


Figure 10 load Versus Slip of the tested specimens

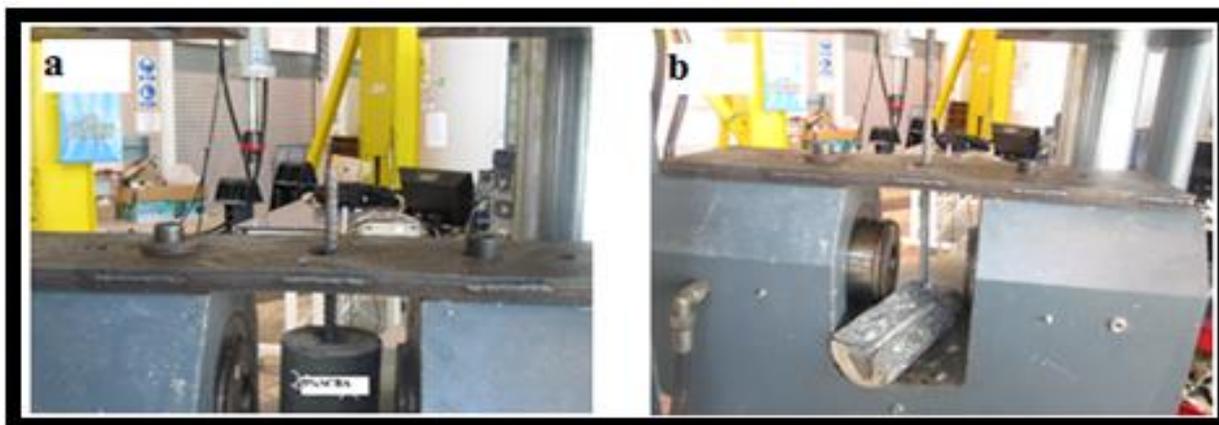


Figure 11: (a) Steel rupture failure (b) Splitting and pullout failure

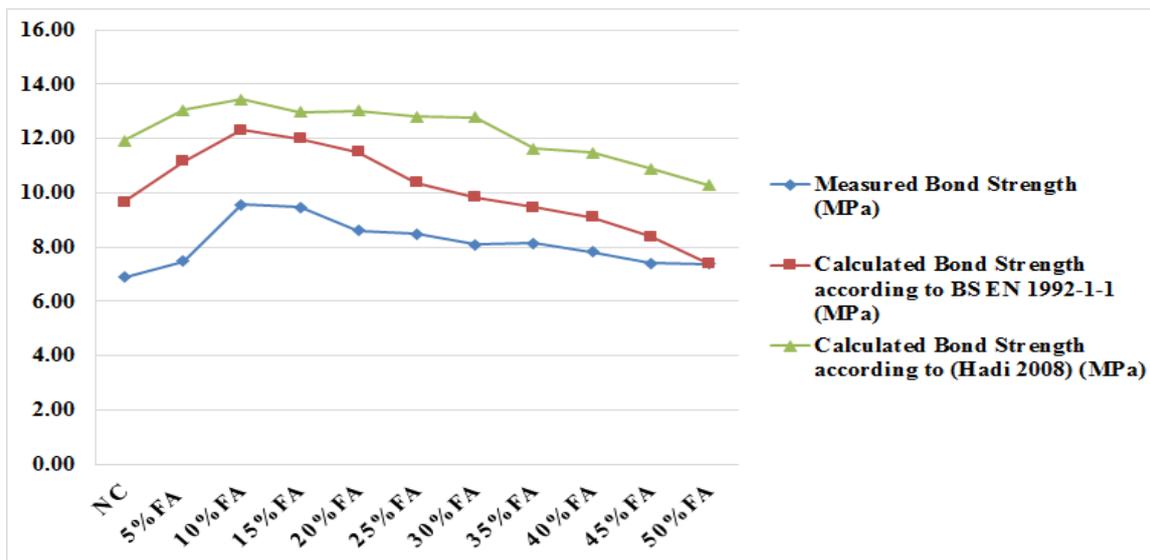


Figure 12 Comparison of the measured and theoretical bond strength

V. CONCLUSIONS

- 1- Regardless the replacement level, inclusion of fly ash in concrete has led to an improvement of workability due to the fineness and spherical shape of its particles.
- 2- Incorporation of fly ash in concrete as CRM significantly enhanced the compressive strength and tensile strength due to the pozzolanic reactivity of the ash and the fineness of the particles which improved the microstructure of the hardened concrete due to packing and filling effect. 10% and 15% fly ash can be considered as optimum levels in this study.
- 3- The bond strength of concrete was drastically improved at 10% and 15 % fly ash replacement levels and these specimens were failed by steel rupture not by concrete failure which means these specimens have not reached their actual bond strength yet. The improvement of bond was about 38% higher than the normal concrete, this percentage would have increased if a steel of high tensile strength was used.
- 4- The bond characteristics are well correlated to the compressive strength of concrete i.e. the higher compressive strength of concrete the higher its bond strength.

VI. ACKNOWLEDGEMENT

The authors would like to extend their acknowledgement to the Universiti Teknologi PETRONAS for providing the facilities and financial support to accomplish this research. It is further extended to Technologist at civil engineering department and centralized analytical laboratory at, Universiti Teknologi PETRONAS for their great contribution and assistance to complete this work.

LIST OF NOTATIONS

- OPC: Ordinary Portland cement.
 CA: coarse aggregate.
 FA: fly ash.
 SP: Superplasticizer.
 F_{bd} : Ultimate Bond Strength (MPa).
 P_{max} : Ultimate axial tensile load (KN).
 ϕ : Reinforcing steel bar diameter (mm) =12 mm for this study.
 l_b : Embedded length (mm) = 200 mm for this study.
 η_1 = Coefficient related to the quality of the bond condition and the position of the bar during concreting
 = 1.0 for condition of good bond.
 = 0.7 for all other cases and for bars in structural elements built with slipforms.
 η_2 = Coefficient related to the bar diameter
 = 1 for $\phi \leq 40$ mm
 f_{ctd} = Design tensile strength
 u = Bond stress
 f'_c = Bharacteristic compressive strength of concrete.
 c = Concrete cover.
 d_b = Nominal diameter of the bar.
 l_d = Embedded length of the reinforced bar.

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