Preliminary study on influence of silica fume on mechanical properties of no-cement mortars

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Abstract. Ordinary Portland Cement (OPC) is widely used as a binder material for various construction application and has been increasing in demand especially in developing countries. However, growing concern about the effect of OPC towards the environment either during production or transportation process captures the researcher’s interest to come out with more sustainable binder material that has similar characteristic as OPC. This paper prescribed the study on the strength performance of no-cement mortar consist of waste materials such as ground granulated blast furnace slag, fly ash and rice husk ash partially replaced with silica fume up until 20% of total binder weight. Eleven different mix designs were fabricated with constant 0.5 water/binder ratio cured under ambient temperature. The mortar specimens of 40 x 40 x 160 mm prisms were prepared and test for their flexural and compressive strength at aged 7, 14 and 28 days after curing. Laboratory tested on strength performance studies indicate that different curing ages exhibit different silica fume replacement level to achieve their optimum strength. Maximum compressive strength achieved at 28 days is 27 MPa at 12% silica fume replacement level.

1. Introduction
Cement has been long used as the binder material in construction but the growing concern on the effect of its production that release carbon dioxide to the environment. Suitable alternative materials that can give sustainable benefit having cementitious properties such as ground granulated blast furnace slag (GGBS) or pozzolan such as metakaolin, fly ash and silica fume have widely studied as cement replacement materials [1,2]. According to Massazza [3], pozzolan can be distinguished into two different meaning, pyroclastic rock that happens in the place called Pozzuoli of Roman times ancient Puteoli around Rome. Secondly, it can be defined by all inorganic materials which release calcium hydroxide (Portland cement clinker) when mixed with calcium hydroxide source (lime) and water. Using industrial or agricultural by-product pozzolans as binder materials can give sustainable benefit toward environment such as reducing waste to be landfill and subsequently give space for other development. The study shows that all these by-product materials and pozzolans give better performance concrete but have relatively slow early hydration [3] and fully utilisation of these materials usually can be improved by adding a particular portion of alkali activator or geopolymer.
technology to accelerate the early hydration. GGBS is a slag by-product form production of pig iron in blast furnace that undergo rapid quenched in water before grinding to fine powder and has been used as binder material since Emil Langen found their latent hydraulic properties in 1862 [4]. The slag production was estimated to be 25 – 30% of crude (pig) iron production and based on that reference, the estimated iron slag output in 2017 was about 300 – 360 million tons [5]. Incorporating high volume GGBS as binder materials in concrete favour the heat of hydration compared to OPC concrete and beneficial for mass concrete application [6] and according to Ibrahim et al. [7], 70% replacement of OPC also improved mechanical properties with 28 days strength comparable with 100% OPC. Pulverised fuel fly ash (PFA) is a residue that flies out from combustion in electric power generating plant and collected by an electrostatic precipitator. Based on Malaysian Energy Commission [8], coal contributed to 42.5% electricity generation mix in 2016 behind gas with 43.5% and it was expected that coal share would increase to 63% exceeding gas in 2020 [9] which subsequently increase the PFA available. The pozzolanic properties of PFA improve the later strength and its spherical microstructure reduce water demand in concrete [10]. Other than that, paddy is the widely planted crop in Malaysia with estimated 674,332 hectares in 2013 including those that planted twice a year [11]. Due to its low bulk density, the large dry volume of rice husk making the disposal process of this material quite challenging as it possesses rough and abrasive surfaces that are highly resistant to natural degradation [12]. In Malaysia, rice husk ash is majorly the residue of rice processing industry as it has been known primarily with its high silica content. Rice husk constitutes about 20% of the rice weight and contains approximately 50% cellulose, 25-30% lignin and 15-20% silica [13]. Since original rice husk ash is coarse, this material needs to be ground to work as a binder. Based on a study by Habeeb and Mahmud [14], increasing grinding time slightly increase the surface area and reducing the particle size. The high surface area of this material resulted from its microporous and multilayers surface. High surface area also may reduce in its workability due to their high water absorption property [15] thus contribute to the limited strength development [16]. RHA and silica fume can be an alternative source of silicon for alkali-activated materials. It was notable by Dembovska et al. [17] that silica fume enhanced the mechanical properties when used not more than 20% from the total binder and the study by Zareei et al. [18], the amount of micro silica added influence the performance of RHA as cement replacement in high strength concrete as it can create more dense concrete by improving the interface transition zone. Other than that, silica fume in ternary or quaternary blends enhance the compressive strength at an early age especially at higher water to binder (w/b) ratio [7]. Consequently, the present paper aims to a preliminary study of the mechanical strength of mortar by fully utilising by-products with cementitious and pozzolanic properties from various industry and replaced with silica fume to improve the mechanical performance of mortar. This subsequently eliminating the need of strong chemical activator and creating an environmental friendly binder.

2. Experimental program

2.1. Materials
The materials used in this study were ground granulated blast furnace slag, pulverised fuel ash, rice husk ash, silica fume and river sand. GGBS, the industrial by-product of iron industry was sourced from a local supplier, YTL Berhad with a specific gravity of 2.86 g/m³ and specific surface area of 4.65 m²/g. PFA was collected from local fuelled power plant precipitator unit. The PFA used in this study have a specific gravity of 2.8 g/m² and a specific surface area of 3.24 m²/g. Other than that, the RHA also was sourced from local rice milling industry, Serba Wangi Sdn.Bhd. The rice husk ash was sieve passing 150 µm prior ground for 30 minutes in laboratory ball mill to achieve a comparable degree of fineness as cement and more than 90% of the ash may pass sieve size of 45 µm [19]. The specific gravity of RHA after been ground was 2.21 g/m³. The densified silica fume (DSF) is filtered powder generated from silicon metals or high purity quartz - ferrosilicon metals and the one that used in this study has a specific gravity of 2.20 g/m² and specific surface area of 20,000 m²/kg. The chemical composition of all binder materials tabulated in Table 1. Saturated surface dry quartzitic
natural river sand was used as fine aggregate with the maximum aggregate size of 5 mm, graded as specified according to the grading limit as in BS 812-103: Part 2 [20]. The fine aggregates have a specific gravity of 2.65 g/m³ and fineness modulus of 3.26. Water used sourced from locally supply tap water.

### Table 1. The chemical composition of binder materials.

| Chemical Compound | PFA | GGBS | RHA | DSF |
|-------------------|-----|------|-----|-----|
| MgO               | 5.94| 5.01 | 0.71| 4.60|
| Al₂O₃             | 17.61| 12.59| 0.26| 0.27|
| SiO₂              | 43.22| 32.62| 90.18| 84.00|
| P₂O₅              | 0.23| 0.01| 1.48| 0.05|
| K₂O               | 1.31| 0.32| 3.97| 2.70|
| SO₃               | -   | -   | 0.35| 0.44|
| Cl                 | -   | -   | 0.54| 2.40|
| CaO               | 11.28| 37.87| 1.51| 0.66|
| CuO               | -   | -   | 0.02| Trace* |
| ZnO               | -   | -   | 0.03| 0.10|
| SeO₂              | -   | -   | Trace* | - |
| Br                | -   | -   | Trace* | - |
| Rb₂O              | -   | -   | 0.01| 0.02|
| SrO               | -   | -   | Trace* | - |
| TiO₂              | 0.88| 0.50| 0.02| 0.09|
| Cr₂O₃             | -   | -   | 0.02| - |
| MnO               | 0.14| 0.25| 0.12| - |
| Fe₂O₃             | 13.73| 2.00| 0.75| 0.54|
| C                 | 1.80| -   | -   | - |
| Na₂O              | 0.43| 0.25| 0.05| 4.70|

*Very small amount – not presented*

2.2. **Mix proportioning and mixing procedure**

Mortar mixture proportion was design based on modified absolute volume method prescribed in ACI 211.1 [21] is given in Table 2 with each mix design nomenclature system of Sₓ where x was the percentage of silica fume replaced from the total binder content. The binder to sand and water to binder ratio for all mix was remained constant at 1:3 and 0.5, respectively. Binder consists of GGBS, PFA, and RHA with a fixed ratio of 0.89:0.09:0.02 replaced with silica fume at an increment of 2% up to 20% of total replacement. The mortar was first prepared by dry mixing of binder materials and fine aggregate in the epicyclic mixer for 5 minutes and slow mixing speed. Quarter from total water was then introduced into the mix and mix for 1 minute. Half of the water was subsequently added and mix for a further minute before stopped to scrape inhomogeneous particles to the middle. Lastly, the rest of the water was added and further mixing for another 1 minutes before stopped, flow table test and placing the mixture into the mould in three layers. For better compaction, each layer was vibrated for 10 seconds on a vibrating table. Moulded samples were left cure in the mould for 24 hours under ambient temperature curing of 28 ± 5°C with relative humidity of 80 ± 5% prior to moist curing by wrapped in a plastic sheet in ambient temperature until testing days.
Table 2. Mix design proportioning.

| Mix | GGBS (kg/m³) | PFA (kg/m³) | RHA (kg/m³) | DSF (kg/m³) | Sand (kg/m³) | Water (kg/m³) | w/b Ratio |
|-----|--------------|-------------|-------------|-------------|--------------|---------------|-----------|
| S0  | 448          | 45          | 10          | 0           | 1511         | 252           |           |
| S2  | 439          | 44          | 10          | 10          | 1510         | 252           |           |
| S4  | 430          | 43          | 10          | 20          | 1508         | 251           |           |
| S6  | 420          | 42          | 9           | 30          | 1507         | 251           |           |
| S8  | 411          | 42          | 9           | 40          | 1505         | 251           |           |
| S10 | 402          | 41          | 9           | 50          | 1504         | 251           | 0.5       |
| S12 | 392          | 40          | 9           | 60          | 1502         | 250           |           |
| S14 | 383          | 39          | 9           | 70          | 1501         | 250           |           |
| S16 | 374          | 38          | 8           | 80          | 1499         | 250           |           |
| S18 | 364          | 37          | 8           | 90          | 1489         | 250           |           |
| S20 | 355          | 36          | 8           | 100         | 1497         | 249           |           |

2.3. Testing methods
The mechanical test conducted in this study consist of compressive and flexural strength test. From each batch of mortar mix design, a total of 3 prisms with 40 x 40 x 160 mm dimension were fabricated for both compressive and flexural strength test and tested based on procedures prescribed in ASTM C349-14 [22]. The result was taken based on the average of 3 prisms for flexural strength and 6 portions of broken prisms from the flexural test were then used for compressive strength test, noted in MPa.

3. Result and discussion

3.1. Flexural strength
The graph in Figure 1. shown a flexural strength result of no-cement mortar at 7, 14 and 28 days. At 7 days of curing, the strength steadily increased up to 4% (S4) replacement level which represented as only 2.85 MPa and notable decrease until the 10% replacement of silica fume. At similar curing age, strength was observed as the silica fume content increase by more than 10% (S12 – S20). Strength performance after 14 and 28 days of curing show similar fluctuated trend with optimum strength at 0% (4.66 MPa) and 10% (5.8 MPa) replacement level respectively. Accelerated strength gain also observed on all specimens except S4 which represent by 4% silica fume addition at 14 days of curing. This confirmed on conclusion stated by [23] the pozzolanic effect of silica fume often occurs after 7 days.
3.2. Compressive strength

From Figure 2, it is shown that different curing age has different silica fume replacement percentage for as optimum compressive strength. At 7 days curing age, the compressive strength of mortar increased up to 4% replacement level of silica fume with 11.4 MPa and gradually decrease as the silica fume increase. The progression of strength can be considered as relatively slow as the pozzolanic reaction took longer time compared when used with OPC as these materials rely on calcium hydroxide from hydration of OPC to increase the rate of hydration [24, 25]. Moreover, slow hydration presented that does not contribute to the decrease in pore space as it still filled with water and resulted in low early strength. When the curing age reached 14 days, the graph seems to fluctuate with the highest compressive strength of 20.19 MPa at 10% replacement level. Accelerated strength gain observed on S0 to S2 at 14 days which represent 10% to 20% silica fume replacement. A similar trend also observed at 28 days of curing up to optimum compressive strength at 12% replacement level with 27.3 MPa but gradually decreasing as the replacement level increased. The increase in silica fume content more than the optimum value may cause the leftover to be act as filler materials rather than reactive mineral compound [26]. When dealing with pozzolanic powders, there might be a filler effect and the sum of filler and pozzolanic effect can be the net effect which contributed both mechanical and durability properties [27]. The rapid increase of strength can be observed from 7 – 14 days of curing. This is in agreement with the finding from Tan [28] which also show accelerated strength gain between the above mention curing aged.

Figure 1. Flexural strength result.
4. Conclusion and recommendation

Based on the mechanical strength result, the no – cement mix containing 10 and 12% silica fume is suitable to be use and binder materials in mortar when early strength is negligible and strength up to 27.3 MPa at 28 days. Furthermore, it was noticeable that silica fume undergoes rapid strength gain between 7 to 14 days. However, further research needs to be conducted to increase the rate of hydration in the early ages and subsequently improve the mechanical strength of the mortar or concrete. Microstructure analysis of hybridisation of these binder materials also needs to be done in future research to study their hardening mechanism.

References

[1] Ramli M B and Alonge O R 2016 Characterization of metakaolin and study on early age mechanical strength of hybrid cementitious composites Construction and Building Materials 121 599–611
[2] Habert G, Lacailierie J B and Roussel N 2011 An environmental evaluation of geopolymer based concrete production: Reviewing current research trends Journal of Cleaner Production 19 1229–38
[3] Massazza F 1998 Pozzolana and pozzolanic cements In Lea’s chemistry of cement and concrete London
[4] Lang E 2002 Blastfurnace cements In Structure Performance of Cement London
[5] U.S. Geological Survey 2018 Mineral commodity summaries 2018: U.S. Geological Survey 200
[6] Han F 2017 Hydration heat of slag or fly ash in the composite binder at different temperatures. Thermochimica Acta, 655 202–10
[7] Ibrahim A, El-Chabib H and Eisa A 2013 Ultrastrength flowable concrete made with high volume of supplementary cementitious materials Journal of Materials in Civil Engineering 25 1579–86
[8] Malaysian Energy Commission 2017 2017 Malaysia Energy Statistic Handbook, Putrajaya
[9] Schernikau L 2016. Economics of the International Coal Trade, Cham, 197 – 198
[10] Thomas M 2007. Optimizing the use of fly ash in concrete. Portland Cement Association 24
[11] Department of Agriculture Malaysia, 2014. *Perangkaan Padi Malaysia (Paddy Statistics of Malaysia)*

[12] Hwang C L and Chandra S 1996 The use of rice husk ash in concrete In *Waste Materials Used in Concrete Manufacturing* 184–234

[13] Hisham B, Putrajaya R and Abdulaziz H 2010 Malaysian Rice Husk Ash – Improving the Durability and Corrosion Resistance of Concrete: Pre-review. *Concrete Research Letters, 1* p 11

[14] Habeeb G A and Mahmud H B 2010. Study on properties of rice husk ash and its use as cement replacement material. *Materials Research* 13 2 185–190

[15] Sathawane S H, Vairagade V S and Kene K S 2013 Combine effect of rice husk ash and fly ash on concrete by 30% cement replacement *Procedia Engineering* 51 35–44

[16] Chindaprasit P, Kanchande P, Sathonsawaphak A 2007 Sulfate resistance of blended cements containing fly ash and rice husk ash *Construction and Building Materials* 21 1356–1361

[17] Dembovska L, Bajare D, Pundiene I and Vitola L 2016 Effect of pozzolanic additives on the strength development of high performance concrete *Procedia Engineering* 1–8

[18] Zareei S A, Ameri F, Dorostkar F and Ahmadi M 2017 Rice husk ash as a partial replacement of cement in high strength concrete containing micro silica: Evaluating durability and mechanical properties *Case Studies in Construction Materials* 7 73–81

[19] Zain M F M, Islam M N, Mahmud F and Jamil M 2011 Production of rice husk ash for use in concrete as a supplementary cementitious material *Construction and Building Materials* 25 798–805

[20] BSI. 1985 BS 812-103.1 Testing aggregates. Method for determination of particle size distribution. Sieve tests, London: *British Standard Institution*

[21] ACI Committee 211 2002 Standard practice for selecting proportions for normal, heavyweight, and mass concrete

[22] ASTM 2002, ASTM C349 Standard test method for compressive strength of hydraulic-cement mortars (Using portions of prisms broken in flexure), *ASTM International*

[23] Ömer Ö C and Sofyanlı Ö 2015 Influence of silica fume on mechanical and physical properties of recycle aggregate concrete *HBRC Journal* 11 157-166

[24] Oner A and Akyuz S, 2007 An experimental study on optimum usage of GGBS for the compressive strength of concrete. *Cement and Concrete Composites* 29 505–14

[25] Zhou X, Slater J R, Wavell S E and Oladiran O 2012 Effects of PFA and GGBS on early-ages engineering properties of Portland cement systems *Journal of Advanced Concrete Technology* 10 74–85.

[26] Neville A 2006. Concrete: Neville’ s Insights and Issues. *Concrete*, 314.

[27] Pedersen B M 2004. *Alkali-reactive and inert Fillers in Concrete. Rheology of fresh Mixtures and expansive Reactions*. Fakultet for ingeniørvitenskap og teknologi.

[28] Tan L.E 2017. *Advanced Self-Healing Geopolymer Composite Derived from Industrial By Product*. Universiti Sains Malaysia