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IJIE

Journal homepage: http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

Mechanical Properties of Self-Compacting Concrete Subjected to Elevated Temperature

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DOI: https://doi.org/10.30880/ijie.2021.13.07.015
Received 16 August 2021; Accepted 2 September 2021; Available online 30 September 2021

Abstract: Self-compacting concrete flows and fills reinforcement gaps and corners of formworks without the need for vibration during the pouring process. The problem associated with the production of self-compacting concrete is the use of a high dosage of cement which necessitates the addition of supplementary cementitious materials to curtail this effect. As a result, the impact of a ternary blended pozzolanic materials on the mechanical properties of SCC exposed to extreme temperatures was investigated. A quantitative research approach was employed and an experimental design method was adopted. The materials used were cement, rice husk ash, metakaolin, and pulverized burnt bricks. Laboratory tests conducted at the hardened stage were compressive strength, weight loss, and ultrasonic pulse velocity of self-compacting concrete subjected to 200°C, 400°C, 600°C, and 800°C elevated temperatures. At 800^{0}C elevated temperature, the result of residual compressive strength shows that SCC produced with addition of the ternary blend at 10 % had a higher value of residual compressive strength of 27.3 % over the control specimens. Control specimens were found to have the least values of weight loss in comparison to the self-compacting concrete produced with the addition of the ternary blend. The result of residual UPV shows that self-compacting concrete produced with addition of the ternary blend at 10 % had a higher value of 8.6 % over the control specimens. When self-compacting concrete is to be produced with a ternary blend of rice husk ash, metakaolin, and pulverized burnt bricks and subjected to an elevated temperature of up to 800°C, 10 wt.% is the optimum cement replacement level.

Keywords: Self-compacting concrete, elevated temperature, ultrasonic pulse velocity, weight loss, supplementary cementitious materials

1. Introduction

Due to the tendency of concrete structures being exposed to conflagration from fire incidences and other applications, researchers and developers of construction materials pay attention to the actual performance of construction materials at elevated temperatures [1], [2], [3]. More specifically, the widespread use of concrete as a construction material for large-scale projects and unique applications raises the risk of concrete being subjected to high temperatures. Because of its superior thermal qualities, concrete remains the ideal material for resisting high temperatures [4], [5], [6].

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Concrete heating led to a series of chemical and physical processes, including an increase in temperature leading to evaporation of pore water close to the heating surface; pore water in the gel then moves to the capillary pores to retain thermodynamic equilibrium. All the pore water evaporates at about 105°C. Dehydroxilation of calcium silicate hydrate (CSH) becomes significant at about this temperature and continues up to 850^0C where CSH will completely hydroxylate [7], [8], [9].

Calcium hydroxide undergoes dehydroxylation at about 400^0C to 600°C. After dehydration of $Ca(OH)_{2,}$ decomposition of the hydration product occurred, and finally, the distraction of gel structure [10]. Similarly, cement paste undergoes thermal expansion up to about 150°C followed by thermal shrinkage up to about 600°C to 800°C; the incompatibility of the thermal strain of the cement paste with the aggregate causes cracking during exposure to elevated temperatures [6], [8], [11]. At about 800°C, concrete specimens usually crumbled, and a further increase in temperature (above 1150°C) caused feldspar to melts. This temperature caused other minerals of cement paste to change to a glass-like phase and lost their integrity [12].

Vasamithaand [13] observed the effect of elevated temperature on high-strength concrete. It is also reported a reduction of about 15 % on the strengths even at a temperature of 200°C. In comparison, the modulus of elasticity dropped by 5 %. The strength of the concrete dropped by about 90 % when exposed to 1000°C irrespective of the type of cement used. In agreement with this, [14] observed that replacing cement with admixtures like palm oil fuel ash and others resulted in a loss in the strength, modulus of elasticity, and ultrasonic pulse velocity of concrete exposed to high temperatures. Supplementary cementitious materials (SCMs) are invariably utilized in the production of self-compacting concrete.

Self-compacting concrete (SCC) flows and fills formwork corners and spaces without the application of external vibration. The flowability is usually achieved by using high-range water reducers (superplasticizers). At the same time, the segregation resistance is achieved by increasing the proportion of powder in the mix design and reducing the percentage of coarse aggregate. Therefore, a higher amount of powder is required in SCC (to control segregation resistance) than conventional vibrated concrete (CVC). This makes SCC more expensive and contributes more to CO_2 emission in the world [15], [16]. The problems associated with a high dosage of cement in SCC production necessitate SCMs to reduce their production cost

Pozzolanic materials such as MK, RHA, and fly ash have been utilized as SCMs in SCC production, with positive results [17], [18], [19], [20]. These materials were used as binary and or multi-blend with cement and had a less significant influence on strength, especially at 28 days of curing and sometimes even improved durability [17], [18], [19], [20].

Rice husk ash, a pozzolanic material rich in silica obtained by calcining rice husk to an average temperature of 650°C to keep the ash in the amorphous phase. The reactivity of RHA is derived from its higher specific surface area compared to cement, although at the expense of workability. When properly treated, RHA at cement substitution rate of 15 wt.% was found to caused an improvement in the transition zone between cement and aggregate and hence improved strength and durability [21]. It can also replace the viscosity modifying agent (VMA) in SCC production [19]. Due to its high specific surface area, the use of RHA as a substitute to cement necessitates a higher dosage of superplasticizers (SP).

Pozzolanic materials can be obtained from clay waste when thermally activated at a temperature range between 500°C to 650°C based on the dehydroxylation temperature [22], [23]. MK is the most reactive calcined clay due to its high hydroxyl groups, leading to disorder formation during activation [24]. MK is a pure, 1:1 clay, and its use as a cement substitute in concrete production can increase the cost of production, as the cost of MK is almost 2 to 3 times that of cement. It also has some other industrial applications [25]. Therefore, its prudence to explore the suitability of using other clay minerals not rich in kaolinite, as pozzolanic materials such as montmorillonite, illite, and or clay waste such as pulverized burnt bricks (PBB). When used as a replacement to cement, MK was found to improve the strength and durability of the concrete. Although it has exerting water demand in comparison to cement [25].

It was established that up to forty percent and beyond cement could be replaced with another pozzolanic material in SCC production [16], [26]. The quality of the resulting concrete is frequently affected when the cement replacement level is increased with a pozzolanic material.

These effects can be eliminated by mixing two or more pozzolanic materials [27]. Therefore, this study is set out to investigate the effect of a ternary blended of RHA, PBB, and MK on SCC properties exposed to an elevated temperature.

2. Materials and Method

2.1 Materials

Portland lime cement of grade 43 was used and tested to meet the requirements of [28]. A coarse aggregate of a diameter 20 mm maximum was used. 40 % of the fine aggregate used passes through a 600 µm sieve. Potable water was used in the experiment. Complaint SP 430 was used as a superplasticizer conforming to the requirement of [29] was used.

Raw rice husk and kaolin clay were calcined at 650°C. The powder collected was ground and sieved to the fineness of approximately 75 µm in a Kaolin processing plant at the industrial layout of the Bauchi metropolis. In the same vein, a clay brick waste was collected, ground, and sieved to the fineness of approximately 75 µm. The chemical and physical compositions of the cement, RHA, MK, and PBB are shown in Table 1.

Table 1 - Physical and chemical composition

Items	**Oxides**	**Oxide content (%)**			
		Cement	**RHA**	**MK**	**PBB**
Lime	CaO	71.30	3.89	0.42	1.87
Silica	SiO_2	17.52	86.30	53.70	52.70
Alumina	Al_2O_3	4.74	0.91	41.70	17.00
Iron Oxide	Fe_2O_3	2.77	0.46	0.86	15.53
Magnesium	MgO	ND	0.14	ND	0.37
Potassium	K_2O	ND	5.04	0.21	2.29
Sulhpor	SO_3	ND	1.23	ND	ND
LOI		3.49	2.34	1.60	8.38
Bulk Density (kg/m^3)		1493	475	666	965
Specific gravity (g/cm^3)		3.46	2.49	2.60	2.18

ND = Not detected

2.2 Methods

2.2.1 Mix Design

BRE approach was used to create Grade 40 NVC, which was then converted into SCC blends through trial and error. The three pozzolanic materials were blended (50 % RHA, 25 % MK, and 25 % PBB) and subsequently used to replace cement at 0, 10, 20, 30, and 40 % and noted as SCC00, SCC10, SCC20, SCC30, and SCC40 respectively. 90 pieces of 100 x 100 x 100 mm^3 were used for the experiment. **Error! Reference source not found.** depicted the mixed design adopted. The mixing sequence adopted is to ensure a complete breakdown of the constituents of the mixture. After mixing for 2 minutes with the dry materials, 2/3 of the concrete water was added and mixed for another 2 minutes. After the remaining mixing, water with the SP was added, and the whole mixture was mixed for another 6 minutes.

Table 2 - Mix Design

S/N	**Mix Designations**	**Quantities of Constituents (Kg)**									
		w/b	**Cement**	**RHA**	**MK**	**PBB**	**F.A**	**C.A**	**Water**	**SP**	**SP (%)**
1	CVC	0.45	460	0.0	0.0	0.0	640	1190	210	0.0	0.0
2	SCC00	0.42	500	0.0	0.0	0.0	900	700	210	08	1.6
3	SCC10	0.42	450	26	13	13	900	700	210	10	2.0
4	SCC20	0.42	400	50	25	25	900	700	210	12	2.4
5	SCC30	0.42	350	74	38	38	900	700	210	14	2.8
6	SCC40	0.42	300	100	50	50	900	700	210	16	3.2

Note: F.A = Fine Aggregate, C.A = Coarse Aggregate

2.2.2 Chemical Composition Analysis

This test determined the oxide content of cement, RHA, MK, and PBB. Minipal 4 energy dispersive X-Ray fluorescence machine was used. Ten grams (10 g) of the powdered sample was weighed and carefully placed on the sample charger of the x-ray fluorescence machine. The major oxides contents, minor oxides contents, and LOI were measured and recorded. The duration of the testing was 100 seconds.

2.2.3 Fresh Properties

The slump flow + T_{500}, L-box, and sieve stability were used to test the filling ability, passing ability, and segregation resistance of SCC at the fresh stage, according to the specifications of [30]. All measurements were conducted 15 minutes from the time water was added to the concrete.

2.2.4 Elevated Temperatures

A ventilated oven capable of heating up to 105°C was used for preheating the cubes that were subsequently exposed to higher temperatures. For elevated temperatures of more than 200°C, an electrically heated furnace capable of heating up to 3000°C temperature was used. At 56 days of curing, the concrete cubes were removed from curing water and dried in air for 24 hours under laboratory conditions. The cubes were pre-dried in a ventilated oven at 105°C temperature for

24 hours before subjecting them to high temperatures. The cubes were then exposed to elevated temperatures from 200 to 800°C for 2 hours. The cubes were cooled at 2°C/min and kept at room temperature for 2 hours. Weight loss, UPV, and residual strength of the cubes were determined.

2.2.5 Compressive Strength

Concrete cubes were positioned so that the load is applied perpendicularly to the direction of pouring loaded at a constant rate of 0.2 MPa/s. The load to failure of each cube was recorded, and the compressive strength was calculated [31]. The residual strength obtained was compared to the strength of the companion specimens.

2.2.6 Ultrasonic Pulse Velocity

Concrete specimens after exposure to the elevated temperature and the companion specimens were subjected to UPV. The transmission duration of the wave through the concrete specimen was recorded. The UPV was calculated according to [32]. The result obtained was used to determine the integrity of the SCC specimens subjected to high temperatures with the companion specimens.

2.0 Results and Discussion

2.1 Physical and Chemical Properties of the Binder

Table 1 presents the chemical and physical properties of cement, RHA, MK, and PBB. RHA has the highest percentage of silica at 86.3 %, followed by MK with 53.7 %, then PBB with 52.7 %, and cement with 17.52 %. This shows that the mixture has enough silica, leading to better strength development, especially at a later age [33]. The alumina found in RHA was insignificant compared to that of MK, which has 41.7 %, followed by PBB with 17 %, and cement with a 4.74 % alumina. This indicates that the mixture will have good strength development at an early age during C-S-H gel formation. The summation of most important oxides content (silica, alumina, and iron oxide) for RHA, MK, and PBB was 87.67, 96.26, and 85.23 %, respectively. These values are within the limit specified by [34] for raw and calcined natural pozzolanic materials and following the work of [35], [36].

Cement has a higher value of specific gravity, 3.46 g/m^3, followed by MK having a value of 2.6 g/m^3, then RHA with 2.49 g/m^{3,} and PBB with 2.18 g/m^3. The three pozzolanic materials have lower values of bulk density compared to cement. The bulk density of PBB is almost two times that of RHA and one and half times that of MK. This indicates that the water required to make a paste of standard consistency will be rise with an increase in the percentage of the blend in the mixture. The results conform to what was reported [19], [36], [37], [38].

2.2 Properties of Fresh SCC

At the fresh stage of the concrete, Table 3 displays the results of slump flow + T500, passing ability, and segregation resistance of SCC_00, SCC_10, SCC_20, SCC_30, and SCC_40 mixes. The flow spread, passing ability, and segregation resistance improved when the replacement rate was increased using the powder blend. However, this requires more superplasticizer and decreased the rate at which the mixture flows. The reference specimens have a slump flow of 665 mm which falls in the second class of slump flow (SF2) as classified by [30]. This concrete is therefore suitable for much normal application. Cement substitution with the blend of RHA, MK, and PBB have improved the slump flow diameter, but SCC classification remained in SF2. The T_{500} values obtained for all the SCC specimens fall within the accepted limits of 2 to 5 as specified by [30].

Table 3 - Properties of fresh SCC mixes

S/N	Mix Designations	Fresh Properties Measured			
		Slump Flow (mm)	**T_{500} (s)**	**Passing Ability(mm)**	**Segregation Resistance (%)**
1	SCC_00	665	3	0.82	4.40
2	SCC_10	675	4	0.80	3.20
3	SCC_20	680	4	0.81	1.20
4	SCC_30	683	4	0.80	0.80
5	SCC_40	685	5	0.84	0.40
	Requirement (EFNARC 2005)	**660 to 750**	**> 2**	**≥ 0.80**	**≤ 20**

Although the substitution of cement with the blend increased the T_{500} time, the results are still within the limit. The L-box values for all the SCC specimens were within the limit of 0.8 to 1.0 specified by [30], and therefore this concrete can conveniently pass through a congested reinforcement section. The reduction in segregation resistance is due to the addition of the blended powder, which has high friction compared to cement. The increase in SP demand due to increasing cement substitution level is because of RHA's high specific surface area and calcined clays compared to cement. This led to an increase in both water and SP demands [33], [39], [40], [41]. This demonstrates that SCC can be made without the use of VMA by raising the powder dosage. These results are in line with the work of [26], [30], [42].

2.3 Weight loss (%) of SCC Specimens Exposed to an Elevated Temperature

Fig. 1 illustrates the percentage reduction in the weight of SCC specimens subjected to 200°C, 400°C, 600°C, and 800°C elevated temperatures. For the entire specimens, weight loss increases linearly with an increase in higher temperature.

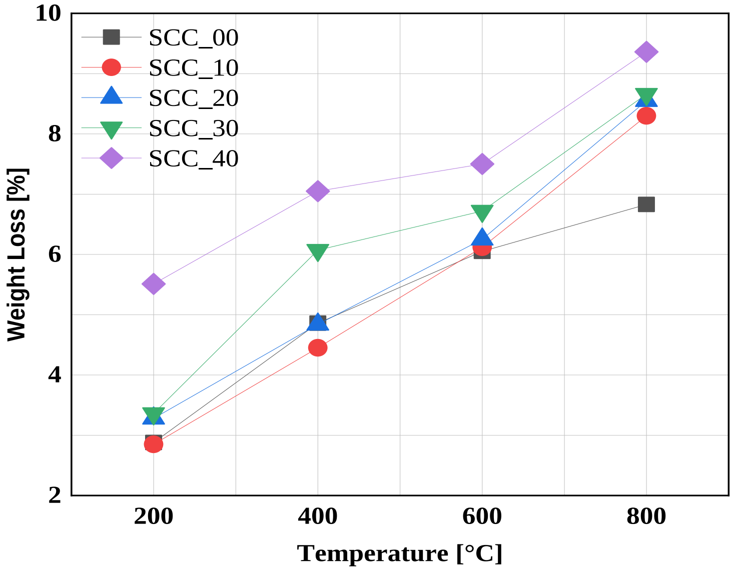

Fig. 1 - A weight loss of SCC specimens

At 200°C, the reference specimens and SCC_10 have the same weight loss of 2.9 %. This is followed by an increase of 2.5 % in SCC_20 and SCC_30, followed by a rise of 6 % in SCC_40. The loss of weight at this stage is perhaps because of the evaporation of pore water in the concrete's capillary. Similarly, at 400°C elevated temperature, SCC_10 recorded the least weight loss of 4.5 % and rose to 7 % in the SCC_00 and SCC_20 specimens. This was followed by another increase of 36 % and 58 % in SCC_30 and SCC_40, respectively. The evaporation of pore water in the concrete gel could cause the specimens' weight loss at this temperature.

At 600°C elevated temperature, SCC_00 has the least loss of 6 % and slightly increased for the remaining samples. At this temperature, the weight loss is due to the dehydration of calcium hydroxide and the expansion of aggregate. Additionally, at 800^0C elevated temperature, the % reduction in weight of SCC_00 is 6.83 %, while that of the remaining specimens is 8.30_% to 9.36_%. Generally, SCC specimens without cement replacement have better resistance to weight loss than those with cement replacement. These findings are in agreement with the work of [13], [14].

2.4 Residual Compressive Strength of SCC Subjected to an Elevated Temperature

Fig. 2 shows the residual strength of SCC specimens subjected to 200°C, 400°C, 600°C, and 800°C elevated temperatures. The compressive strength of all the concrete decreases with an increase in exposure to elevated temperature. At 200°C exposure temperature, SCC_20 and SCC_40 have the highest residual strength. This is then followed by a decrease of about 8 % in the remaining concrete. The residual strength measured at this temperature for all the specimens was greater than the specimens cured in water. This could be due to pore water evaporation in the concrete's capillary pores, making the concrete more homogenous. However, 400°C, SCC_30 has the highest residual compressive strength and decreased 5% in SCC00, and a dropped off of 9 % and 16 % in SCC_20 and SCC_40, respectively. The strength of SCC specimens of this class is generally less than the companion specimens cured in water except for SCC_30, which is 3 % greater than the companion specimen. The decrease in strength could result from dehydration of calcium silicate hydrate, making cement lose its binding properties [13]. At 600°C, SCC_30 recorded the highest residual compressive strength. This is then followed by a slight steady decrease of 4 % in the remaining specimens. The residual compressive strength of SCC exposed to this temperature was about 45 % less than the companion specimens. This is an indication of the large dehydration of calcium silicate hydrate in the mixture. Similarly, SCC_10 has the greatest residual compressive strength at 800°C, followed by SCC_00, SCC_20, and SCC_30. SCC_40 suffered the greatest loss of the residual strength of about 91%. SCC_00 has a 77 % drop in strength at this temperature, while the remaining specimens had a 71 to 91 % reduction. The disintegration of hydration products and the disruption of gel structure caused by the high temperature may be the reason for the loss in residual compressive strength. These findings are in line with the work of [13], [14].

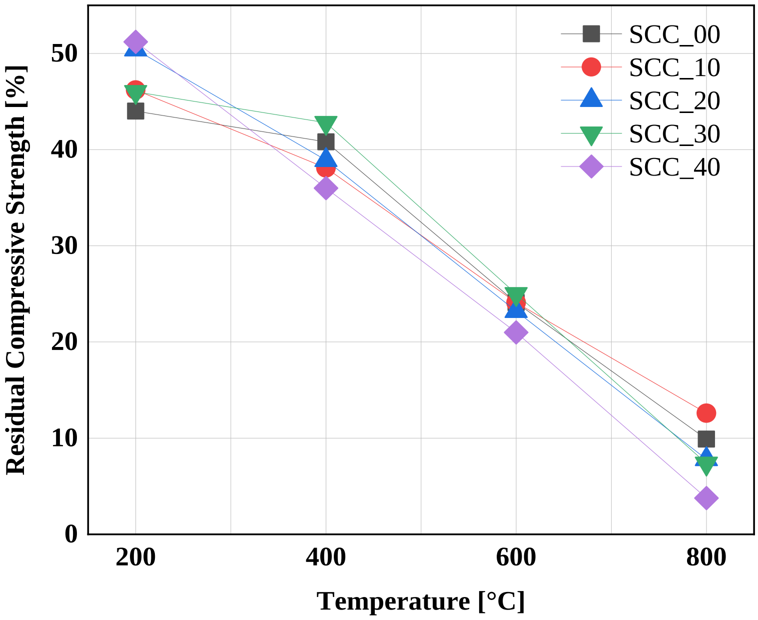

Fig. 2 - Residual compressive strength of SCC specimens

2.5 Residual UPV of SCC Specimens Exposed to an Elevated Temperature

Fig. 3 presents the UPV residual values for SCC specimens exposed to increased temperatures of 200°C, 400°C, 600°C, and 800°C. The residual UPV values for the concrete decrease linearly with increasing the elevated temperature.

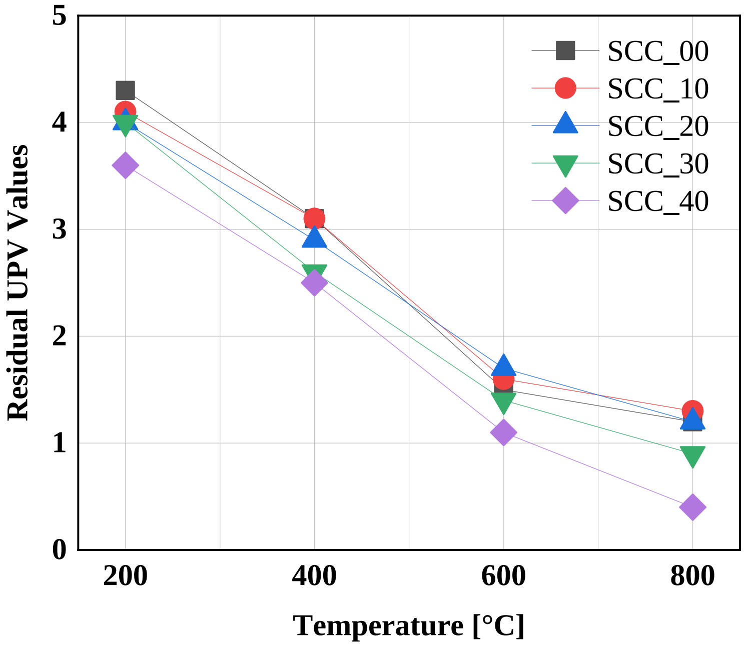

Fig. 3 - Residual UPV

At 200°C elevated temperature, all the concrete specimens have good quality, and SCC_00 recorded the highest UPV value. SCC_00 and SCC_10, on the other hand, exhibit doubtful quality at 400°C, while the rest specimens have low quality. Similarly, the quality of the concrete was found to be poor for all specimens at 600°C and 800°C. At 200°C, 400°C, 600°C, and 800°C, the percentage reduction in UPV of SCC 00 is 2.6, 29.5, 71.8, and 73.7 percent, respectively.

While that of the remaining specimens is 8.5 to 16.9 % at 200°C, 32.3 to 41.7 at 400°C, 62.8 to 74.5 % at 600°C, and 72.1 to 89.9 % at 800°C. This shows that SCC_00 has better residual UPV values at elevated temperatures than the remaining specimens except for SCC_10. The result obtained is similar to the findings of [43], [44]. Table 4 shows the ranges of quality of concrete based on the value of UPV (m/s) provided by [45].

Table 4 - Concrete quality as a function of UPV

UPV(Km/s)	Quality of concrete
Above 4.5	Excellent
3.5 to 4.5	Good
3.0 to 3.5	Doubtful
2.0 to 3.0	Poor
Below 2.0	Very poor

2.6 Relationship between Compressive strength and UPV of SCC Specimens

Fig. 4 shows the correlation between compressive strength and ultrasonic pulse velocity of SCC specimens exposed to elevated temperatures and companion specimens cured in water. The Pearson's product-moment (r) coefficient of correlation for all the specimens was determined and presented.

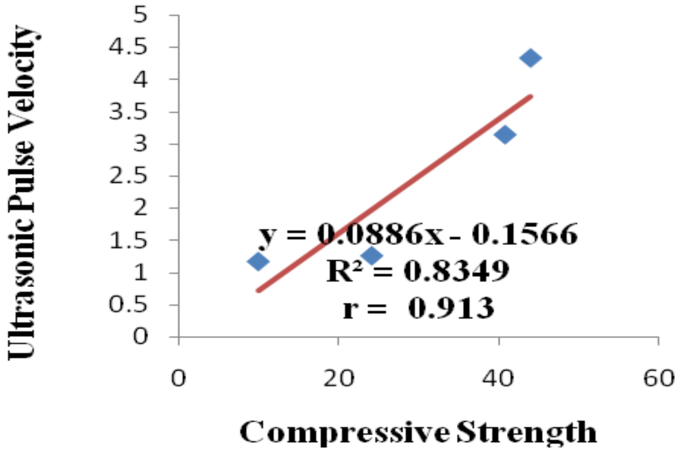

Fig. 4 - Correlation between compressive strength and UPV

Pearson's coefficient was found to be 0.913. This indicates a strong positive relationship between the two tests' results for all the different replacement levels. Therefore, both methods can conveniently be used to determine the integrity of concrete exposed to an elevated temperature.

3 Conclusion

The specific gravity and bulk density of RHA, MK, and PBB ranged between 4 to 7%, 475 to 965kg/m^3, and 2.18 to 2.49g/cm3. Based on their chemical compositions, the materials were pozzolanic. Flow spread, passing ability, and segregation resistance of fresh SCC produced with RHA, MK, and PBB were determined to be 665mm to 685mm, 0.80mm to 0.84mm, and 0.4 percent to 4.4 percent, respectively. This concrete can be used to cast congested horizontal and vertical slabs and columns. This concrete is also suitable for normal concreting works. Elevated temperatures up to 800^{0}C cause a reduction in compressive strength between 71 to 91 % for SCC specimens produced with a ternary blend of RHA, MK, and PBB. While that of SCC without cement replacement was 77 %, up to 10% of cement can be replaced with a ternary blend of RHA, MK, and PBB to produce concrete with improved resistance to elevated temperature.

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