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THE COMPRESSIVE AND FLEXURAL STRENGTHS OF SELF-COMPACTING CONCRETE USING RAW RICE HUSK ASH

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Abstract

This study investigates the compressive and flexural strengths of self-compacting concrete incorporating raw rice husk ash, individually and in combination with other types of mineral additives, as partial cement replacement. The additives paired with raw rice husk ash were fine limestone powder, pulverized fuel ash and silica fumes. The mix design was based on the rational method where solid constituents were fixed while water and superplasticizer contents were adjusted to produce optimum viscosity and flowability. All mixes were designed to achieve SF1 class slump-flow with conformity criteria $\geq$ 520 mm and $\leq$ 700 mm. Test results show that 15% replacement of cement using raw rice husk ash produced grade 40 concrete. It was also revealed that 30% and 45% cement replacements using raw rice husk ash combined with limestone powder and raw rice husk ash combined with limestone powder and silica fume respectively, produced comparable compressive strength to normal concrete and improved flexural strengths.

Keywords: Self-compacting Concrete, Rice husk ash, Additives, Strengths.

1. Introduction

Self-compacting concrete (SCC) was first developed in 1988 by Professor Okamura intended to improve the durability properties of concrete structures [1]. SCC is defined as concrete that is able to flow and consolidate under its own weight, completely fill the formwork even in the presence of dense reinforcement, whilst maintaining homogeneity and without the need for any additional compaction [2]. In order to do this, SCC requires higher paste content and lower coarse aggregate fraction compared to conventional vibrated concrete, and uses superplasticizer [1]. These would ensure high deformability of paste and resistance to segregation.

In order to reduce the use of cement in a high paste concrete, inert or reactive mineral additives have been employed as partial cement replacement. The use of mineral additives in SCC was also found to produce other advantages such as enhancement of SCC properties in fresh and hardened states, reuse of industrial and agricultural byproducts in concrete production and reduction of greenhouse gases into the atmosphere.

There have been extensive studies done on the use of the more common mineral additives such as; fine limestone powder [3-6], pulverized-fuel ash [7-10], silica fume [11-14], hence their effects on SCC are somewhat predictable. However, lesser interests are shown on other types of mineral additives due to various factors such as; the availability of certain mineral additives are localized to particular regions only, transportation problems and heterogeneity of the additives chemical components.

Rice husk ash (RHA) is an agricultural by-product obtained from burning of the husk under controlled temperature of below 800 ºC. The process produces about 25% ash containing 85% to 90% amorphous silica plus about 5% alumina, which makes it highly pozzolanic. It was reported that for about 1000 kg of paddy milled, 55 kg of RHA was produced. India, being the highest rice-producing country, generated about 20 million tons of RHA annually [15]. But, according to Habeeb and Fayyadh [16], its application in concrete production is yet to be realized due to lack of knowledge. Farooque et al. [17] reported that, in Bangladesh huge quantity of RHA generated during par-boiling process at rice milling plants ended in landfills because there was no systematic effort to utilize the ash commercially.

Numerous investigations on the use of RHA in concrete production have been done, and all produced positive results [16-19]. However, the ash used in most of the investigations was produced under controlled laboratory condition. Hence, its applicability under massive concrete production level is unclear. This study incorporates rice husk ash which is the by-product of rice husk used as fuel for the parboiling process in paddy mill. The ash is used in its original state without undergoing further treatment such as grinding and sieving hence it is termed ‘raw’ rice husk ash (RRHA).

The optimum level of cement replacement with RHA was found to be between 10% and 20% [18]. In order to realize higher level of replacement, RRHA is blended with fine limestone powder (LP), pulverized fuel ash (FA) and silica fume (SF). Multiple mineral additives replacement of cement was also found able to offset possible deleterious effects of single mineral additive replacement [7]. Therefore, the present study investigates the effects of raw rice husk ash on compressive and flexural strengths of self-compacting concrete; when used in binary blend with ordinary Portland cement and in ternary and quaternary blends with ordinary Portland cement, fine limestone powder, pulverized fuel ash and silica fume.

2. Materials and Mixture Proportions

2.1. Materials

The basic constituent materials of SCC are similar to those of normal vibrated concrete i.e. paste (cement, mineral additive and water) and aggregates (sand and gravel or crushed rocks). The base paste material used in this study was Type 1 ordinary Portland cement (OPC), manufactured by Tasek Cement Corporation Berhad. Mineral additives used were, as shown in Fig. 1, LP, FA, SF and RRHA, all of which were obtained from local sources. The chemical composition and physical properties of OPC and mineral additives are shown in Table 1.

Fine limestone powder Pulverized-fuel ash

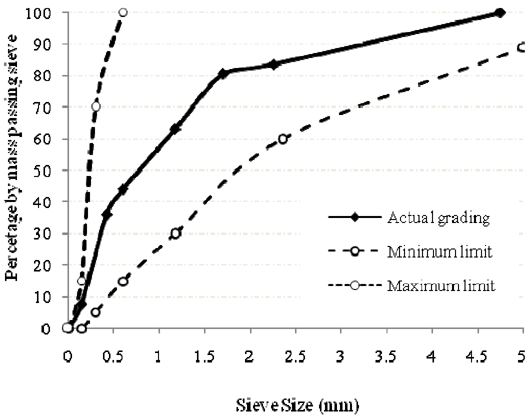
Silica fume Raw rice husk ash

Fig. 1. Mineral Additives used to replace Cement (OPC); Fine Limestone Powder (LP), Pulverized-Fuel Ash (FA), Silica Fume (SF) and Raw Rice Husk Ash (RRHA).

Table 1. Physical and Chemical Properties of Ordinary Portland Cement (OPC), Fine Limestone Powder (LP), Pulverized-Fuel Ash (FA), Silica Fume (SF) and Raw Rice Husk Ash (RRHA).

	OPC	LP	FA	SF	RRHA
Oxide Composition (%)					
SiO_2	21.28	1.84	56.2	90.36	92.99
Al_2O_3	5.60	1.37	20.17	0.71	0.18
Fe_2O_3	3.36	-	6.69	1.31	0.43
CaO	64.64	52.98	4.24	0.45	1.03
MgO	2.06	0.42	1.92	-	0.35
SO_3	2.1	0.08	0.49	0.41	0.10
Physical properties					
Specific gravity	3.15	2.80	2.20	2.10	2.16
Blaine (m^2/kg)	340	443	290	20,000	351

Washed river sand (S) was sieved to produce fine aggregate with maximum particle size of 4.75 mm. Sand gradation test was performed in accordance with ASTM C136 standard but the overall sand grading limits, as shown in Fig. 2, were based on BS 882. Subsequently, additional limits for grading categorise sand into C (coarse), M (medium) and F (fine). The sand used for this study falls under category M (medium), which is suitable for most structural and non-structural applications.



* Sand grading limits – from BS 882

Fig. 2. Grading of Fine Aggregate (Washed River Sand) Performed in accordance with ASTM C136 Standard.

Crushed granite (G) was graded between 4.75 mm to 12.5 mm, and was used as coarse aggregate material. The superplasticizer (SP) used was ADVA 181; a high range water-reducing polymer-based admixture formulated in accordance with BS5075 Part 3:1985 specification. Mixing water used was piped water supplied by the local authority.

2.2. Mixture proportion

The principles for the selection and proportioning of SCC constituents were based on guidelines laid out by the European Project Group [2]. The mix design, on the other hand, was based on the rational method proposed by Okamura and Ouchi [1]. Based on the rational mixed design method, solid materials were fixed while mixing water and SP dosage were adjusted so as to achieve optimum viscosity and flowability. Slump-flow tests were used to evaluate the ease of flow of fresh concrete under unconfined condition, or generally termed as flowability. This study adopted the slump-flow SF1 class whereby the conformity criteria were ≥ 520 mm and ≤ 700 mm [2].

The mixture compositions are as shown in Table 2. The control mix maintains 475 kg/m³ of OPC without replacement. The binary mix (BM) incorporates raw RRHA replacing 15% of OPC. The ternary mixes (TM1, TM2 and TM3) incorporate blends of RRHA with LP, FA or SF replacing 30% of OPC. The quaternary mixes (QM1, QM2 and QM3) incorporate triple combinations of raw RHA with LP, FA and/or SF replacing 45% of OPC. The aggregate content constitutes the remaining volume fraction calculated based on one cubic meter of concrete. The aggregate comprises of 60% sand and 40% granite.

Table 2. Mixture Proportions for the Control Mix, Binary Mix, Ternary Mixes and Quaternary Mixes.

Mix	Label	OPC	LP	FA	SF (kg/m³)	RRHA	S	G
NM	CM	475	-	-	-	-	1047	712
BM	C/RHA	403.75	-	-	-	71.25	1027	698
TM1	C1/LP/RRHA	332.5	71.25	-	-	71.25	1023	695
TM2	C1/FA/RRHA	332.5	-	71.25	-	71.25	1007	686
TM3	C1/SF/RRHA	332.5	-	-	71.25	71.25	1012	688
QM1	C2/LP/FA/RRHA	261.25	71.25	71.25	-	71.25	1004	681
QM2	C2/LP/SF/RRHA	261.25	71.25	-	71.25	71.25	1006	683
QM3	C2/FA/SF/RRHA	261.25	-	71.25	71.25	71.25	994	676

* OPC - ordinary Portland cement; LP – fine limestone powder; FA – pulverized fuel ash; SF – silica fume; RRHA – raw rice husk ash; S – washed river sand; G – crushed granite, NM: Control mix without OPC replacement, BM: Binary mix – 15% of OPC replaced by RRHA, TM: Ternary mixes – 30% replacement of OPC with two additive components comprising LP, FA, SF and RRHA, QM: Quaternary mixes – 45% replacement of OPC with three additive components comprising LP, FA, SF and RRHA

3. Experimental Programme and Test Procedures

Seven SCC mixes were prepared comprising of one binary mix BM (C/RRHA), three ternary mixes TM1 (C1/LP/RRHA), TM2 (C1/FA/RRHA) and TM3 (C1/SF/RRHA) and three quaternary mixes QM1 (C2/LP/FA/RRHA), QM2 (C2/LP/SF/RRHA) and QM3 (C2/FA/SF/RRHA). One control mix (NM) was also designed using the same proportioning as the SCC mixes. The control mix is used to compare the performances of SCC mixes without RRHA and without the combined mineral additives.

Immediately after mixing, slump-flow tests were carried out on each mix in accordance with BS EN 12350-8:2009. The wet mixes were then cast into 100 mm cubic moulds and 100 mm x 100 mm x 500 mm prismatic moulds. The test specimens were left to stand for 24 hours, after which they were demoulded and immersed in water for curing. Dry density, compressive strength, flexural strength tests were carried out after 7, 14, 28, 60 and 90 days of water curing. Fig. 3 shows the schematic drawing of 3-point flexure test on prismatic specimen.

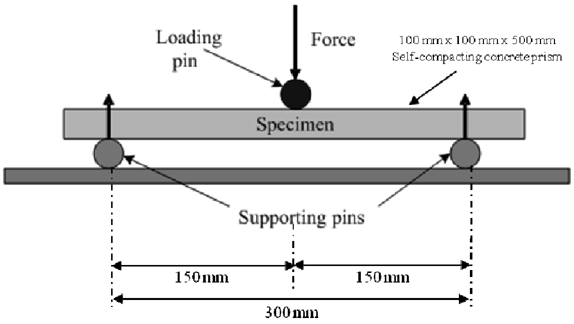


Fig. 3. Schematic Drawing of 3-Point Flexure Test on 100 mm × 100 mm × 500 mm Self-Compacting Concrete Prismatic Specimen.

All tests were done in accordance with the respective BS EN standards i.e.:

- Testing Fresh Concrete Part 8: Self-compacting Concrete – Slump-flow test (Draft BS EN 12350-8) [20].
- Testing Hardened Concrete Part 7: Density of hardened concrete (BS EN 12390-7:2009) [21].
- Testing Hardened Concrete Part 3: Compressive strength of test specimens (BS EN 12390-3:2009) [22].
- Testing Hardened Concrete Part 5: Flexural strength of test specimens (BS EN 12390-5:2009) [23].

4. Results and Discussion

4.1. Fresh SCC properties

Fresh SCC properties are shown in Table 3. The control mix requires 185 L/m³ of mixing water and 10.5 L/m³ of SP dosage, while the binary mix C/RRHA (BM) requires 255 L/m³ of mixing water and 10.5 L/m³ of SP dosage to produce 640 mm slump-flow. This shows that 15% replacement of OPC with RRHA causes an increase in mixing water requirement by around 38% while the SP requirement remains the same. Mineral additives increase the initial viscosity at rate that depends on its fraction ratio while the amount of change depends on its particle shape, texture and distribution [24]. As shown in Table 1, RRHA possesses higher Blaine area compared to OPC.

Table 3. Fresh Properties of Control Mix, Binary Mix, Ternary Mixes and Quaternary Mixes.

Mix	Label	**Mixing Water** (L/m³)	**SP** (L/m³)	**Slump-Flow** (mm)
NM	CM	185	10.5	-
BM	C/RRHA	255	10.5	640
TM1	C1/LP/RRHA	255	11.3	640
TM2	C1/FA/RRHA	245	11.0	600
TM3	C1/SF/RRHA	255	10.0	640
QM1	C2/LP/FA/RRHA	255	7.5	660
QM2	C2/LP/SF/RRHA	255	7.5	685
QM3	C2/FA/SF/RRHA	275	11.25	610

According to Farooque et al. [17], close examination using SEM photomicrograph suggests that RHA particles are highly porous and as shown in Fig. 4, possess honeycombed structure. Since the ratio of surface area to volume increases exponentially with particle irregularity [5], this has a predominant effect on fresh SCC. When particles exhibit large specific area (high Blaine value), large amount of water is absorbed on the particles' surface resulting in less water available to lubricate and to disperse the particles. This phenomenon produces negative effect on flowability of fresh SCC. In order to increase flowability while without lowering the viscosity excessively that might cause segregation of coarse aggregate, water is added to the mix. The rate by which water is added when 15% of OPC was replaced with RRHA is shown to be 38% higher as compared with the control mix, which was without replacement.

30% replacement of OPC with RRHA in combination with equal mass of LP, FA and SF is shown to exhibit similar requirement for water and SP with that of the binary mix. It could, therefore be assumed that LP, FA and SF additions do not affect water and SP requirement at 30% replacement level. However, 45% replacement of OPC produces different fresh property behaviours. Quaternary mixes C2/LP/FA/RRHA (QM2) and C2/LP/SF/RRHA (QM3) show substantial reduction in SP requirement compared to the control mix. It was reported that LP was the best additive when it replaced part of cement, where higher fluidity was exhibited caused by dilution effect [7]. On the other hand, quaternary mix C2/FA/SF/RRHA (QM3) is shown to exhibit high demand for both water and SP. The extreme fineness of SF particles coupled with the cellular shape and porosity of RRHA particles result in high surface which increases mix viscosity.

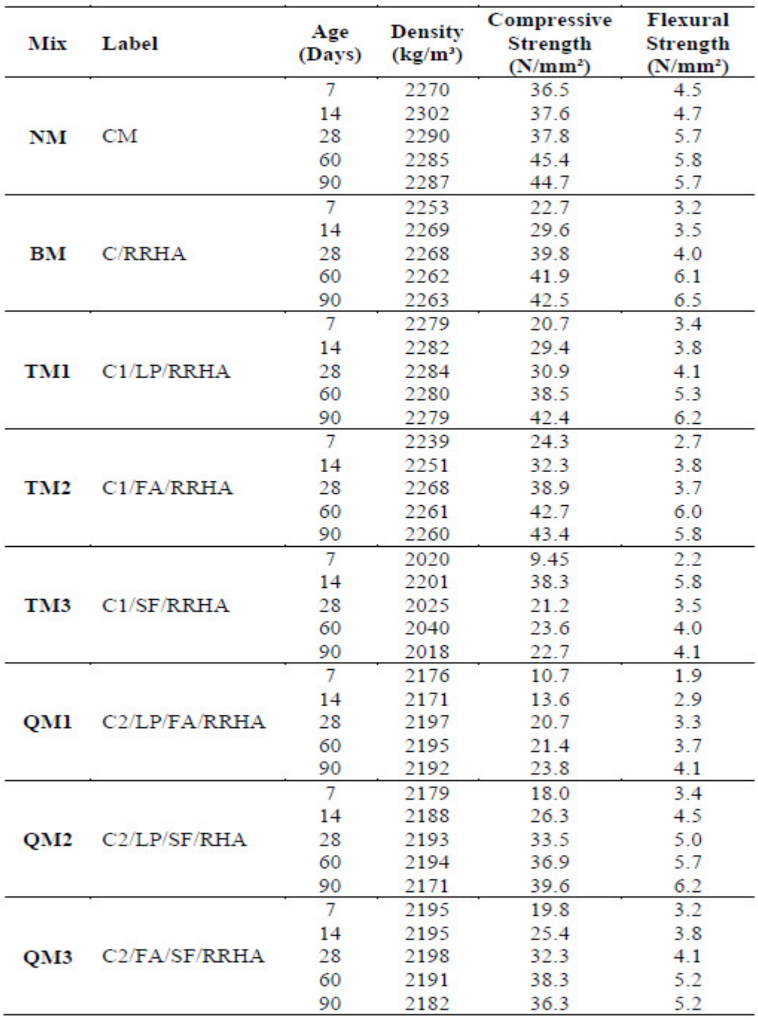
Fig. 4. Typical SEM Image of RHA Particle showing Honeycombed Structure.

4.2. The hardened properties

The hardened properties are shown in Table 4. Tests carried out after 90 days reveal that the control mix (CM) obtained compressive and flexural strength values of 44.7 MPa and of 5.7 MPa respectively, while the binary mix BM obtained 42.5 MPa and 6.5 MPa respectively. This shows that replacing 15% of OPC with RRHA produces slightly lower compressive strength but higher flexural strength as compared to the control mix. Similar results are also shown when 30% of OPC was replaced with LP/RRHA and FA/RRHA blends. However, 30% replacement with SF/RRHA blend produced substantially lower compressive and flexural strengths.

Two quaternary mixes QM2 and QM3 are shown to produce comparable results with the control mix. But, quaternary mix QM1 is shown to exhibit substantially lower strength as compared with the control mix.

Table 4. The Hardened Properties of the Control Mix (NM), Binary Mix (BM), Ternary Mixes (TM) and Quaternary Mixes (QM).



Mix	Label	Age (Days)	Density (kg/m^3)	Compressive Strength (N/mm^2)	Flexural Strength (N/mm^2)
NM	CM	7	2270	36.5	4.5
		14	2302	37.6	4.7
		28	2290	37.8	5.7
		60	2285	45.4	5.8
		90	2287	44.7	5.7
BM	C/RRHA	7	2253	22.7	3.2
		14	2269	29.6	3.5
		28	2268	39.8	4.0
		60	2262	41.9	6.1
		90	2263	42.5	6.5
TM1	C1/LP/RRHA	7	2279	20.7	3.4
		14	2282	29.4	3.8
		28	2284	30.9	4.1
		60	2280	38.5	5.3
		90	2279	42.4	6.2
TM2	C1/FA/RRHA	7	2239	24.3	2.7
		14	2251	32.3	3.8
		28	2268	38.9	3.7
		60	2261	42.7	6.0
		90	2260	43.4	5.8
TM3	C1/SF/RRHA	7	2020	9.45	2.2
		14	2201	38.3	5.8
		28	2025	21.2	3.5
		60	2040	23.6	4.0
		90	2018	22.7	4.1
QM1	C2/LP/FA/RRHA	7	2176	10.7	1.9
		14	2171	13.6	2.9
		28	2197	20.7	3.3
		60	2195	21.4	3.7
		90	2192	23.8	4.1
QM2	C2/LP/SF/RHA	7	2179	18.0	3.4
		14	2188	26.3	4.5
		28	2193	33.5	5.0
		60	2194	36.9	5.7
		90	2171	39.6	6.2
QM3	C2/FA/SF/RRHA	7	2195	19.8	3.2
		14	2195	25.4	3.8
		28	2198	32.3	4.1
		60	2191	38.3	5.2
		90	2182	36.3	5.2

4.3. Compressive and flexural strengths development

The characteristics of compressive and flexural strengths development for the control mix and the binary mix are shown in Fig. 5. The control mix exhibits high early strength gain in both compression and flexure. According to the US Portland Cement Association [25], high cement content results in high heat development in 18 to 72 hours which accelerates the hydration process. Once the heat liberation period is over, the hydration process is allowed to progress at its pace. As shown in Fig. 5, slight retardation of strength development is observed between 7 days and 28 days (compressive strength case) and between 7 days and 14 days (flexural strength case). Compressive and flexural strengths continue to increase at moderate rate up to 60 days and 28 days respectively, after which no strength increase was recorded.

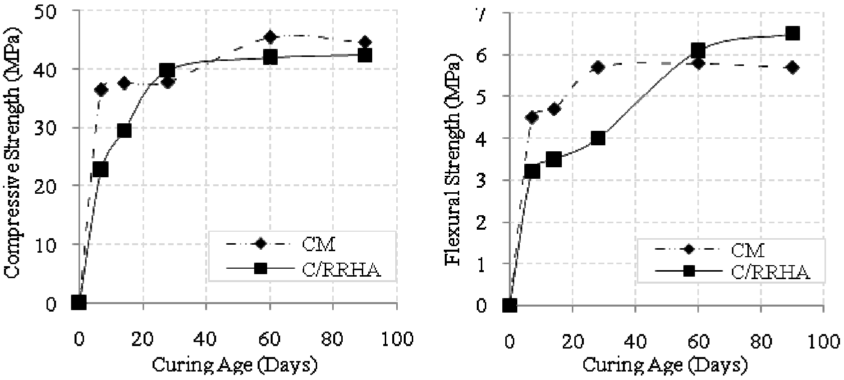


Fig. 5. The Compressive and Flexural Strengths Development for the Control Mix and Binary Mix.

The binary mix (C/RRHA) exhibits moderate early strength of 22.7 MPa (in compression) and 3.2 MPa (in flexure). Strength development increases at high rate from 7 days to 28 days (compressive strength case) and from 7 days to 60 days (flexural strength case). One of the functions of mineral additive such as RRHA is to regulate the cement content so as to reduce heat of hydration [2]. When heat of hydration is reduced, strength development at early age is also reduced. It is well known that pozzolanic reaction occurs after the hydraulic reaction of cement because the silicate content of pozzolanic materials only react with hydroxide produced during the hydration of cement. However, the rate of pozzolanic reaction is influenced by chemical content as well as particle specific area. This is because the mechanism of pozzolanic hydration/reaction is dissolution and diffusion controlled process [26]. Therefore, particle size and surface area plays an important role in the rate of reactivity of pozzolanic material in alkaline solution. It is shown in this experiment that RRHA has high specific area which contributes to high rate of hydration. Furthermore, as shown in Table 1, RRHA has high content of amorphous silica (> 90%) which makes it highly reactive. Thus, the combination of physical property and chemical composition contributes to RRHA's high rate of strength development resulting in comparable 90-day compressive strength and improved flexural strength as compared with the control mix.

The characteristics of compressive and flexural strengths development for the ternary mixes incorporating 30% replacement of OPC with RRHA, in combination with equal mass of LP, FA and SF are shown in Fig. 6. TM1 mix (C1/LP/RRHA) exhibits consistency in the rate of strength development with successive high strength gain throughout the 90 days period. This indicates the inclusion of LP into OPC/RRHA blend, while replacing equal mass of OPC produces comparable compressive strength and improved flexural strength as compared with the control mix. LP addition is also shown able to affect high rate of strength increase throughout the duration of 90 days. Although near-inert, the fineness of its particles is known to produce pore-filling effect which densifies concrete's micro-structure [2]. As shown in Table 4, the dry density of TM1 at 90 days is only 8 kg/m³ lower than the dry density of the control mix. This is besides the fact that concrete with RRHA addition tends to be lighter than normal concrete due to RRHA's lower bulk density (70 kg/m³ to 110 kg/m³) compared to OPC (830 kg/m³ to 1650 kg/m³).

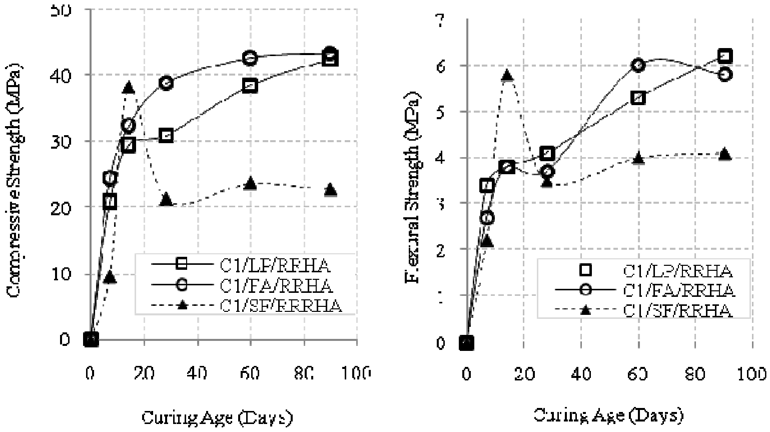


Fig. 6. Compressive and Flexural Strengths Development for Ternary Mixes.

Ternary mix TM2 (C1/FA/RRHA) exhibits better consistency in compressive strength development and higher 90 days compressive strength (43.4 MPa) as compared with TM1 mix. This indicates a synergy of inter-particle interaction between OPC, FA and RRHA which enhances compressive strength property. However, although flexural strength tests reveal high rate of increase in the first 14 days and from 28 days to 60 days, there are evidences of strength retardation in the periods between 14 and 28 days and after 60 days onwards. Thus, both compressive and flexural strengths development seems to reach peak value at around 60 days, after which there is a tendency for the strength to be reduced.

The ternary mix TM3 (C1/SF/RRHA) exhibits substantial strength gain on the first 14 days followed by similar substantial reduction up to 28 days. After the 28 days drop period marginal development is shown resulting in overall low strength attainment. It is thus shown that the inclusion of LP and FA into OPC/RRHA blends produces comparable strength as the control mix; whereas the inclusion of SF into the same blend produces negative results.

The characteristics of compressive and flexural strengths development for quaternary mixes are as shown in Fig. 7. The quaternary mix QM2 (C2/LP/SF/RRHA) exhibits identical compressive and flexural strength development characteristics i.e. moderate early strength gain followed by relatively high strength increase throughout the 90 days period. Its compressive strength of 39.6 MPa at 90 days is comparable with that of the control mix, while its flexural strength of 6.2 MPa is higher.

Quaternary mix QM3 (C2/FA/SF/RRHA) exhibits similar compressive and flexural strengths development with QM2 up to 60 days. But from 60 days to 90 days, there is marginal reduction in compressive strength while flexural strength is unchanged. This is similar scenario as TM2, where strength development is shown to reach its peak at around 60 days. Since both mixes involve the inclusion of FA, it may be deduced that FA affects the strength development phenomenon that occurs at around 60 day period. On the other hand, the quaternary mix QM1 (C2/LP/FA/RRHA) exhibits low overall strength development suggesting that the blend of LP/FA/RRHA is unsuccessful in replacing OPC at 45% level.

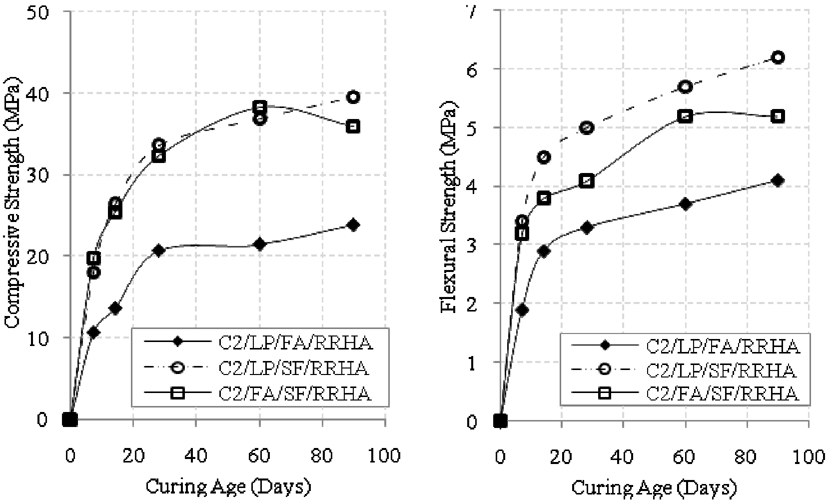


Fig. 7. Compressive and Flexural Strengths Development for Quaternary Mixes.

5. Conclusions

This study shows that raw rice husk ash can be used to replace cement in self-compacting concrete. 15% replacement of OPC with RRHA, 30% replacement with two mineral additive components (LP/RRHA) and 45% replacement with three mineral additive components (LP/SF/RRHA) produce comparable compressive strength as the control mix and improved flexural strength. 30% replacement of OPC with two mineral additive components (FA/RRHA) and 45% replacement with three mineral additive components (FA/SF/RRHA) produce comparable compressive and flexural strengths as the control mix. In general, RRHA addition exhibits better performance in flexure as compared to its performance in compression.

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