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RESONANT FREQUENCY IN POLYPROPYLENE FIBRE REINFORCED CONCRETE (PFRC) WITH POZZOLANIC MATERIALS

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Abstract. In this study, the resonant frequency of polypropylene fibre reinforced concrete (PFRC) under three different curing conditions was investigated and the influences of fly ash (PFA) and silica fume (SF) on PFRC under the same curing condition were also studied. The experiments were carried out in the Heavy Laboratory of City University of Hong Kong. Four types of concrete mixes were tested. A total of 24 concrete specimens were prepared. Test results show that the resonant frequency can be affected by the presence of polypropylene fibres, partial replacement of cement by silica fume or pulverized fly ash, and curing condition.

Keywords: concrete, resonant frequency, polypropylene fibres, pozzolans, silica fume, pulverized fly ash, curing.

1. Introduction

High-strength concrete with compressive strength higher than 41,0 N/mm^2 (6000 psi) is being used in the construction of buildings, and other reinforced and prestressed concrete structures. One major drawback of high-strength concrete is that it is brittle with low tensile strength and strain. The failure of high-strength concrete structure may be sudden in particular when it is subjected to loadings like earthquake and blast. An ideal solution to overcome the disadvantage of high-strength concrete is to add fibres in the concrete so as to convert it into a comparatively ductile material and to avoid sudden failures [1, 2].

Being used in discontinuous form, fibres are distributed inside the concrete matrix. Therefore they can be considered as secondary reinforcement for controlling cracks due to humidity or temperature changes and cracks due to tensile stress [1].

The use of fibrous reinforced concrete has still been in the research phase in the structural building materials area. However, most of the fibres used extensively today are carbon, glass, natural fibres, polypropylene and steel. The last two are the most widely used in conventionally placed concrete [3]. Considering the economical and corrosive reasons, the polypropylene fibres have a high potential to be used in future [4]. So far, very limited research on behaviour of concrete members reinforced with polypropylene fibres can be found.

According to ACI Committee 544 [5], some pozzolans, such as pulverized fly ash (PFA) and silica fume (SF) would have a great contribution in fibre reinforced concrete (FRC). The incorporation of pozzolans can improve the mechanical properties of concrete in both fresh state and hardened state. Besides, not only the pozzolans may affect the properties, the curing condition can also alter the properties of hardened concrete [6].

The objectives of this study are (1) to analyze the resonant frequency of PFRC under the influence of the partial substitution of cement with pulverized fly ash (PFA) and silica fume (SF), and (2) to investigate the influence of the curing conditions on resonant frequency of PFRC with and without partial replacement of cement by PFA and SF.

2. Details of experiments

All the experiments were carried out in the Heavy Structures Testing Laboratory in the Dept of Building & Construction at City University of Hong Kong, Hong Kong.

2.1. Concrete mixes

Four different mixes were designed and given in Table 1. The mix proportions of the four mixes were very similar. Three mixes (Mixes CP, CPF and CPS) were made using polypropylene fibres containing about 0,2% by volume of the concrete. The polypropylene fibres were produced from the W.R. Grace (Hong Kong) Limited, the fibres are alkali resistant, non-absorptive, and completely non-corrosive. Some general physical properties are shown in Table 2.

Table 1. Mix proportion of each mix

Mix type / Concrete components (kg/m^3)	Mix C Ordinary Portland cement concrete (OPC)	Mix CP Fibre reinforced concrete (PFRC)	Mix CPF Fibre reinforced fly ash concrete	Mix CPS Fibre reinforced silica fume concrete
Cement	360	360	324	324
Coarse aggregates 20 mm 10 mm	 720 400	 720 400	 720 400	 720 400
Fine aggregates	700	700	700	700
Water	180	180	180	180
Polypropylene fibre	-	2,58	2,58	2,58
Fly ash	-	-	36	-
Silica fume	-	-	-	36
*Superplasticier Daracem 100 (5cc./kg)	1800	1800	1800	1800

Note: * The amount of Daracem 100 is dependent on the cement used.
5cc. of Daracem 100 will be used per 1kg of cement.

Mixes CPF and CPS contained 10% fly ash and 10% silica fume respectively to replace the same amount of cement (by weight). The water/cement ratio of 0,5 was used for each mix. Also the same amount of superplasticizer (Daracem 100) was added into the mix so as to facilitate easy mixing. Mixing of concrete was done in a rotary mixer.

Table 2. Properties of polypropylene fibres [7]

Specific gravity	0.91
Absorption	None
Modulus of elasticity	3500 N/mm^2
Melt point	160^{o}C
Ignition point	590^{o}C
Alkali, acid, salt resistance	High

2.2. Concrete specimens and curing

Six 100×100×500 mm plain concrete beams for each of the four mixes were cast. Being covered with plastic sheets for 24 hours to prevent evaporation of water from the fresh concrete, the specimens were then demoulded after 24 hours. Afterwards, they were stored in different places under different curing conditions. Three different conditions were adopted to cure the hardened concrete specimens and they are described as follows.

Condition a

Air curing at 25°C and humidity 65%

Condition 27w

Water curing at 27°C for 7 days and then return to air curing at 25°C and humidity 65%

Condition 38w

Water curing at 38°C for 7 days and then return to air curing at 25°C and humidity 65%

2.3. Resonant frequency test

Malhotra *et al.* [8] stated that it was used almost exclusively in the laboratory and involved the determination of the natural frequencies of vibration of concrete prisms. The frequency of a vibration applied to a body was equal to one of the natural frequency of vibration of that body. This condition was called resonance. This frequency could be obtained due to the maximising amplitude of the vibration in the body. However, the frequency should be fundamental frequency that was the lowest resonant frequency of the concrete. Table 3 recommends the range of frequencies on different size of specimens.

Table 3. Range of longitudinal fundamental resonant frequencies of concrete prisms and cylinder specimen [9]

Size of specimens (mm)	Approximate range of frequency (Hz)
150 x 150 x 750	1700 – 3000
150 x 150 x 700	2000 – 3200
100 x 100 x 750	1700 – 3000
100 x 100 x 500	3000 – 4500
100 x 100 x 300	5000 – 7000
150 x 300 cylinder	5000 – 7000

The test apparatus, as required by BS 1881 [10], includes a vibrator which vibrates the concrete at the point of contact at a given frequency, and a sensor which picks up the vibration at the other end of the specimen. Generally, longitudinal mode of vibration will be tested in this study. That means the compressive waves travel through a specimen in the direction parallel to its length.

The resonant frequency test is complied with the BS 1881 [10]. The resonant frequency was corrected to nearest 0,5 Hz. The procedures of resonant frequency test can be summarised as follows.

1. The beam specimen was clamped or balanced at its centre on the fixed support.

2. Grease was used to provide a good contact between the vibrator/pick-up rods and the concrete surface.

3. The vibrator and the pick-up rods were moved so that both of them were just in contact with the centre of the end surfaces of beam. Then the supports were locked by using the knurled clamping screws.

4. The apparatus was switched on. The output voltage control was adjusted to 1 volt.

5. With reference to Table 3, the resonant frequency of the test beams was within the 3000–4500 Hz range.

6. The frequency was gradually increased.

7. The frequency of vibrator should be varied until a resonance was obtained and the frequency was recorded. Resonance was recognized when the indicator showed a peak response and a large and sharp sound would be produced.

8. In order to obtain the fundamental frequency accurately, the frequency of excitation was varied below and above the resonance frequency and to test whether the indicator showed another peak response.

3. Results & discussion

All experimental results are given in Table 4 and some variations are plotted in Fig 1.

3.1. Development of resonant frequency

Referring to Fig 1, the resonant frequency of all mixes on the test beams increased rapidly at 3 days and then the increase was retarded after that. Table 5 shows the percentage change of the development of resonant frequency relative to that at 28 days.

From Table 5, the frequencies at 3 days and 7 days were about 93% and 98% of that at 28 days while the frequency at 91 days was 1% more than the frequency of 28 days. The frequency increases with age because the reaction products of hydration decrease the porosity with age. At early ages, the reactants (cement and water) are enough to allow the hydration to progress in a fast rate. Therefore the resonant frequency increases rapidly. However, the amount of reactants decreases with age, the gain in resonance frequency increases slowly at later ages (28 and 91 days).

3.2. Resonant frequency of PFRC

From Fig 1, mix CP shows slightly lowered resonant frequency than mix C. With the addition of polypropylene fibres in Portland cement concrete, the resonant frequency is slightly decreased under the three examined curing conditions. Table 6 shows the percentage change of mix CP when compared with mix C.

From Table 6, the resonant frequency of mix CP indicates no significant difference but the frequency of mix CP is slightly lower than those of mix C. The percentage change varies from –1,8% to –0,3%. The reason is that the resonant frequency test is dependant upon both the vibration frequency of the sample and the density. The density of polypropylene fibres is lower than those of aggregate and the mortar. As a result, the presence of polypropylene fibre in the Portland cement concrete produces lowered resonance frequency than the control specimens (without fibre). However, the volume fraction of polypropylene fibre is only 0,2%, its effect is not considerable.

3.3. Resonant frequency of PFRG under the influence of PFA

From Fig 1, with the partial replacement of cement by PFA in PFRC, mix CPF gives slightly lowered resonant frequency than the mix CP at early ages (3 and 7 days) while a slightly higher resonant frequency is shown in mix CPF than mix CP at later ages (28 and 91 days). Table 7 shows the percentage change of mix CPF compared with mix CP.

Table 4. Experimental results of resonant frequency

Curing condition	Mix	Average resonant frequency (Hz)			
		3 days	7 days	28 days	91 days
Air (a) curing	C	3500	3628	3764	3794
	CP	3436	3598	3713	3731
	CPF	3430	3580	3707	3732
	CPS	3538	3675	3798	3820
27w curing	C	3593	3789	3862	3905
	CP	3580	3760	3875	3919
	CPF	3553	3722	3913	3945
	CPS	3644	3834	3930	3980
38w curing	C	3707	3873	3940	3977
	CP	3676	3855	3928	3951
	CPF	3622	3826	3934	3972
	CPS	3732	3908	3990	4102

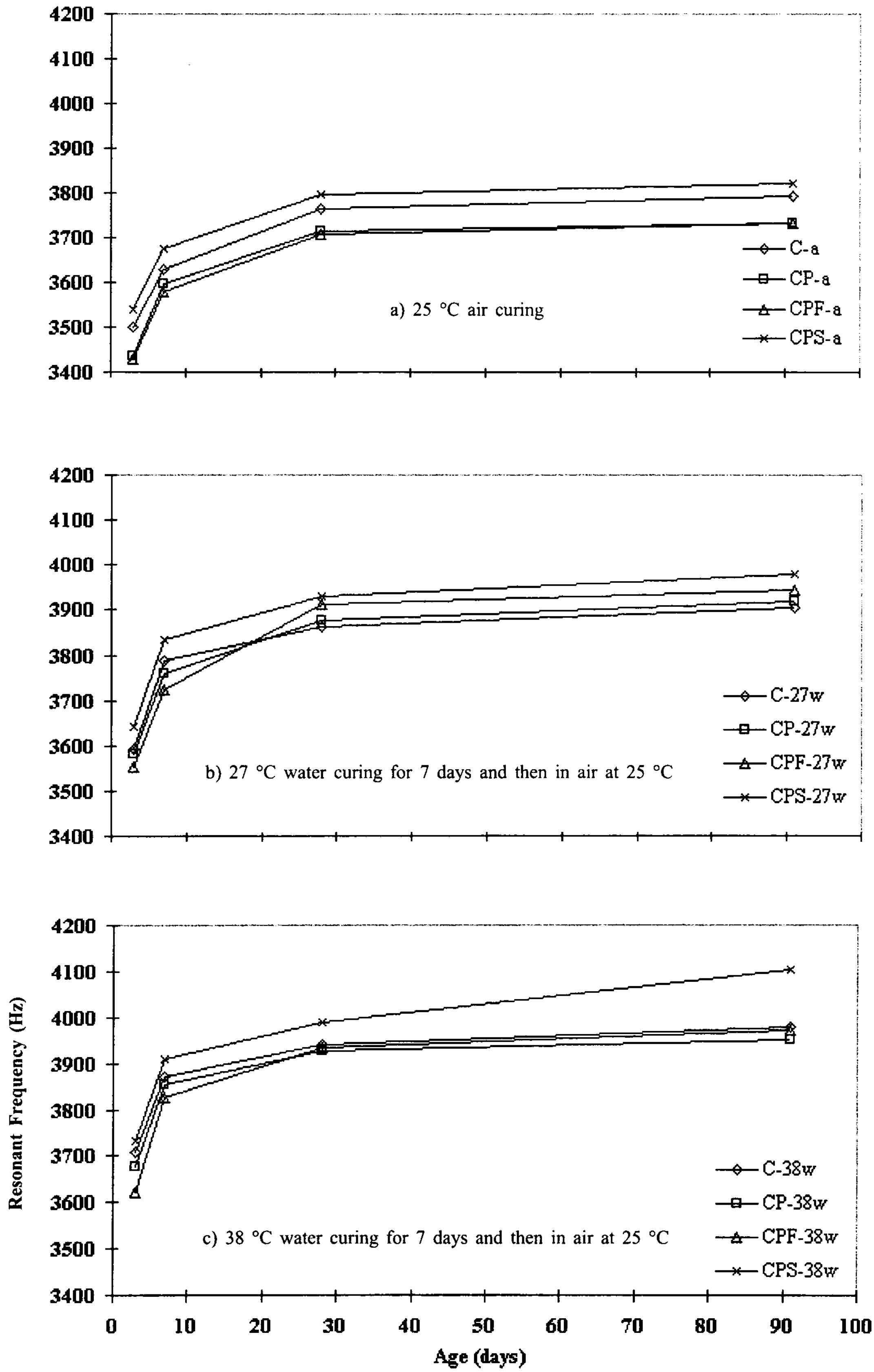

Fig 1. Variation of resonant frequency of all mixes with age under different curing conditions

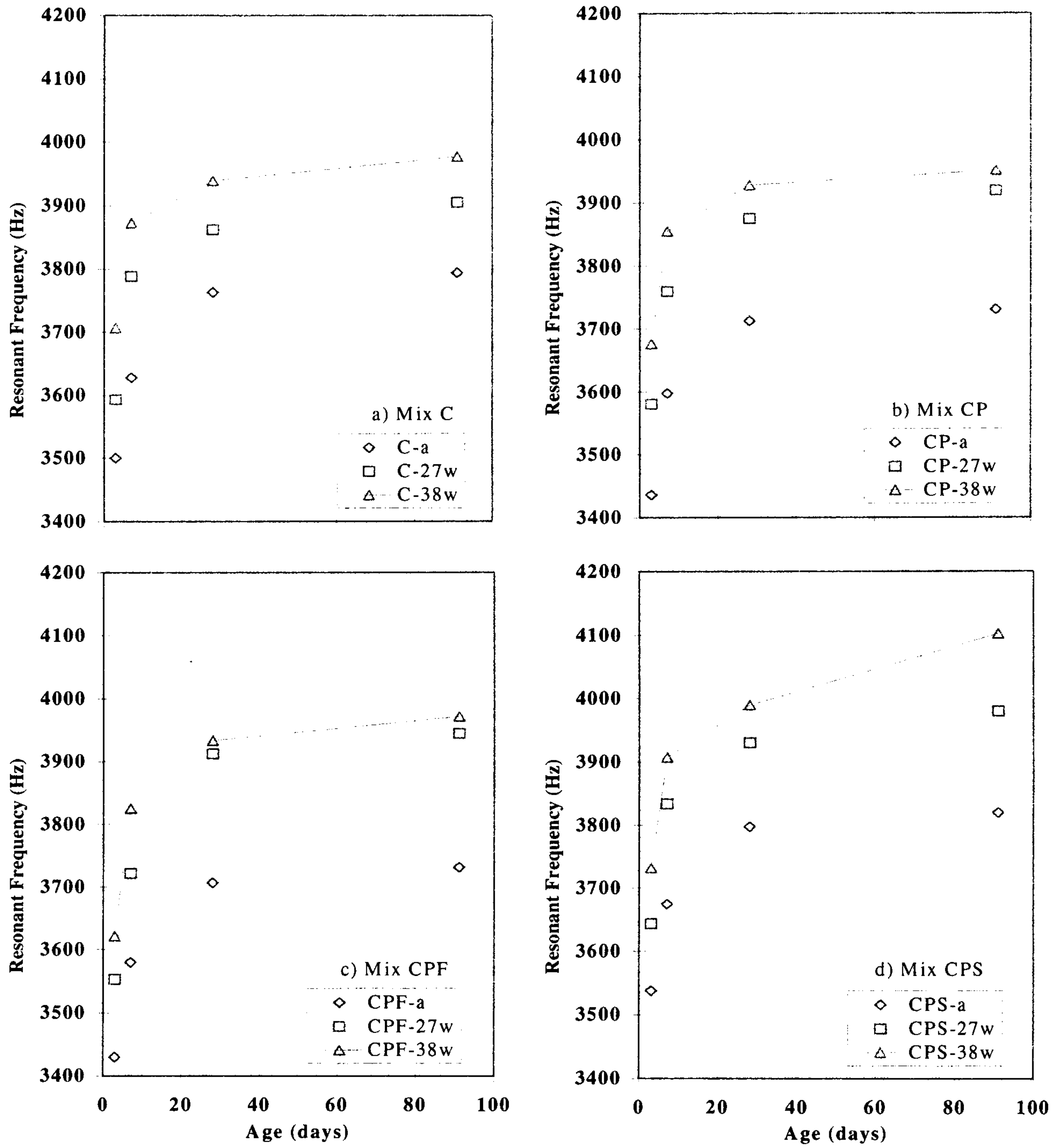

Fig 2. Comparison of resonant frequency of a) mix C, b) mix CP, c) mix CPF and d) mix CPS under three curing conditions with age

Table 5. The percentage change of resonant frequency relative to 28 days for each mix

Mix	Curing conditions*	Resonant frequency (Hz)				Percentage change compared with 28 days of each mix under each curing condition			
		3 days	7 days	28 days	91 days	3 days	7 days	28 days	91 days
C		3500	3628	3763,5	3794	93 %	96 %	100 %	101 %
CP	a	3436	3597,5	3712,5	3730,5	93 %	97 %	100 %	100 %
CPF		3430	3580	3707	3731,5	93 %	97 %	100 %	101 %
CPS		3538	3675	3797,5	3820	93 %	97 %	100 %	101 %
C		3593	3788,5	3862	3905	93 %	98 %	100 %	101 %
CP	27w	3580	3760	3875	3919	92 %	97 %	100 %	101 %
CPF		3553	3722	3913	3945	91 %	95 %	100 %	101 %
CPS		3643,5	3834	3930	3980	93 %	98 %	100 %	101 %
C		3706,5	3872,5	3939,5	3977	94 %	98 %	100 %	101 %
CP	38w	3676	3855	3928	3951	94 %	98 %	100 %	101 %
CPF		3622	3825,5	3933,5	3972	92 %	97 %	100 %	101 %
CPS		3732	3907,5	3990	4102	94 %	98 %	100 %	103 %

Notes: * a = air curing at 25°C and 65% RH. at all ages
27w = water curing at 27°C for 7 days and then air curing at 25°C and 65% RH.
38w = water curing at 38°C for 7 days and then air curing at 25°C and 65% RH.

Table 6. The percentage change of resonant frequency of mix CP relative to mix C $\left(\frac{F_{CP}-F_C}{F_C}\times 100\%\right)$

Ages (days)	Curing conditions		
	a (air curing at 25°C at all ages)	27w (water curing at 27°C for 7 days and air curing)	38w (water curing at 38°C for 7 days and air curing)
3	-1,8 %	-0,4 %	-0,8 %
7	-0,8 %	-0,8 %	-0,5 %
28	-1,4 %	0,3 %	-0,3 %
91	-1,7 %	0,4 %	-0,7 %

where F_C represents the resonant frequency of mix C
F_{CP} represents the resonant frequency of mix CP

Table 7. The percentage change of resonant frequency of mix CPF relative to mix CP $\left(\frac{F_{CPF}-F_{CP}}{F_{CP}}\times 100\%\right)$

Ages (days)	Curing conditions		
	a (air curing at 25°C at all ages)	27w (water curing at 27°C for 7 days and air curing)	38w (water curing at 38°C for 7 days and air curing)
3	-0,2 %	-0,8 %	-1,5 %
7	-0,5 %	-1,0 %	-0,8 %
28	-0,1 %	1,0 %	0,1 %
91	0,0 %	0,7 %	0,5 %

where F_{CP} represents the resonant frequency of mix CP
F_{CPF} represents the resonant frequency of mix CPF

Under air condition, mix CPF produces slightly lowered frequency (about 0,2% and 0,5% at 3 and 7 days respectively) than mix CP but there is no difference at 91 days. Under 27w and 38w conditions, mix CPF also gives slightly lowered values than mix CP at early ages but it is about 0,5% higher than mix CP at later ages (28 and 91 days).

In fact, the water condition enhances the pozzolanic effect of PFA in FRC so as to increase the value of resonant frequency. At early ages, PFA affects the reaction rate of calcium aluminates and calcium silicate. The resonant frequency increases in later ages due to the pozzolanic reaction of fly ash. The activity of fly ash contributes to reduce the porosity at later ages. In the long term, the alkali soluble silica and alumina from the glass phase of PFA react with lime to form the calcium aluminate and calcium silicate hydrates which assist to reduce the concrete porosity. The result is similar to the effect of PFA on ordinary cement concrete [11].

3.4. Resonant frequency of PFRC under the influence of SF

From Fig 1, with the partial replacement by SF on PFRC, the resonant frequency of mix CPS is always higher than that of mix CP (without silica fume) at all ages under each curing condition. Table 8 shows the percentage change of mix CPS comparing with mix CP.

As can be seen in Table 8, the frequency increases from 1,4% to 3,8% under the presence of SF on PFRC. There are two reasons for this. Firstly, because of the small particle size, SF acts as filler to fill the spaces between cement grains [12]. This results in a reduction in the size of the individual pores and voids in the paste. Secondly, more calcium hydroxide is converted to calcium silicate hydrate due to the pozzolanic reaction. Hence, the calcium silicate hydrate is more gel-like and much denser than that of Portland cement, therefore the pores are greatly reduced and enhances the resonant frequency.

3.5. Effect of curing conditions

Fig 1 also shows that the all mixes are under different conditions. The frequency of each mix increases in the following order: a < 27w < 38w. From this figure, concrete specimens stored under water curing for 7 days gives higher resonant frequency than air curing. Table 9 shows the relative percentage of resonant frequency of each mix relating to those concrete mixes under 27w condition at 28 days.

Under the air curing, excess water is evaporated from the concrete so more voids are formed in the paste. The relative percentages of air curing are smaller than that of the 27w condition. As a result, the concrete mix stored under air curing gives a lower resonant frequency than under water curing.

From Fig 2, air curing shows negative effect on both OPF and PFRC mixes when compared with 27w condition. For instance, the reduction percentages at 28 days for air curing are 3%, 4%, 5% and 3% for mix C, mix CP, mix CPF and mix CPS respectively compared with 27w condition. Neville [13] stated that hydration at a maximum rate can proceed only under condition of saturation. Under the 27w and 38w conditions, more water filled-spaces are filled by hydration products at early age.

Although the water-cured specimens are kept in air curing after 7 days, the resonant frequency is still higher than that of air-cured specimens. Even if there is water loss after 7 days for the water-cured specimens, the matter content is still higher than that of the air cured specimens. Therefore air curing reduces the resonant frequency of the concrete mixes compared with 27w condition and it implies that water curing for 7 days is very important for the hydration either at early or later ages.

Besides, the warm water curing (38°C) provides a good curing condition for the hydration. Table 9 shows that the relative percentage under 38w condition is always higher than the 27w condition for different ages. This implies that 38°C warm water curing accelerates the hydration of cement to fill the void rapidly, so 38w curing condition encourages the gain in the frequency of each mix. Also, from Figure 2, the increased percentages of resonant frequency at 28 days for 38w conditions are 2%, 1%, 1% and 2% for mix C, mix CP, mix CPF and mix CPS respectively compared with 27w condition. Therefore the warm water method (38w condition) reports a positive effect on OPC, fibre concrete and fibre concrete with pozzolans, and this improves the development of resonant frequency.

4. Conclusions

According to the experimental results, it can be concluded that:

- The presence of polypropylene fibres gives little effect on the resonant frequency. The resonant frequency of the fibre concrete shows less than 1% increase when

Table 8. The percentage change of resonant frequency of mix CPS relative to mix CP $\left(\frac{F_{CPS}-F_{CP}}{F_{CP}}\times 100\%\right)$

Ages (days)	Curing conditions		
	a (air curing at 25°C at all ages)	27w (water curing at 27°C for 7 days and air curing)	38w (water curing at 38°C for 7 days and air curing)
3	3,0 %	1,8 %	1,5 %
7	2,2 %	2,0 %	1,4 %
28	2,3 %	1,4 %	1,6 %
91	2,4 %	1,6 %	3,8 %

where F_{CP} represents the resonant frequency of mix CP

F_{CPS} represents the resonant frequency of mix CPS

Table 9. The relative percentage of resonant frequency of each mix under different curing conditions relating to those mixes under 27w condition at 28 days

Mix	Curing conditions *	Relative percentage compared with the strength under 27w condition at 28 days			
		3 days	7 days	28 days	91 days
C		90,6%	93,9%	97,4%	98,2%
CP	a	88,7%	92,8%	95,8%	96,3%
CPF		87,7%	91,5%	94,7%	95,4%
CPS		90,0%	93,5%	96,6%	97,2%
C		93,0%	98,1%	100%	101,1%
CP	27w	92,4%	97,0%	100%	101,1%
CPF		90,8%	95,1%	100%	100,8%
CPS		92,7%	97,6%	100%	101,3%
C		96,0%	100,3%	102,0%	103,0%
CP	38w	94,9%	99,5%	101,4%	102,0%
CPF		92,6%	97,8%	100,5%	101,5%
CPS		95,0%	99,4%	101,5%	104,4%

Notes: * a = air curing at 25°C and 65% RH. at all ages
27w = water curing at 27°C for 7 days and then air curing at 25°C and 65% RH.
38w = water curing at 38°C for 7 days and then air curing at 25°C and 65% RH.

compared with that of the plain concrete.

- Under the influence of PFA, the resonant frequency is slightly decreased at early ages but then is increased at later ages compared with the ordinary fibre concrete.
- The advantage of using PFA in plain concrete would also apply to PFRC. The mechanical properties of fibre concrete are improved by the pozzolanic reaction of PFA.
- The resonant frequency of SF fibre concrete is higher when compared to that of ordinary fibre concrete.
- Polypropylene fibre reinforced concrete incorporating silica fume is benefited from the improvement provided by SF to plain concrete. The mechanical properties of fibre concrete are improved by the pozzolanic reaction of SF.
- Concrete specimens cured under 25°C air curing indicates decreased resonant frequency compared with 27w curing conditions. The drying effect in the air curing decreases the gain in the development of mechanical properties.
- The air curing method reduces the gain in the rate of pozzolanic reactions of PFA and SF compared with 27w condition therefore the mechanical properties are not improved significantly by the pozzolanic reaction under air curing.
- The initial water curing for 7 days is essential for improvement of the mechanical properties at all ages compared with air curing because the early water curing appears to provide a good condition for the hydration and the pozzolanic reaction.
- The specimens cured under 38w curing condition show higher mechanical properties than those specimens cured under 27w curing condition. The warm water temperature (38°C) accelerates the gain in the mechanical properties. Also, the pozzolanic reactions of PFA and SF are also be enhanced. The mechanical properties of fibre concrete with pozzolans improve under 38w condition compared with 27w condition.

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