Influence of Micro Steel and Polypropylene Fibres on the Dynamic Properties and Porosity of Ultra High Performance Concrete

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Abstract

Ultra-high Performance Concrete (UHPC) is a special type of concrete with extraordinary potentials in terms of strength and durability performance. This paper aims to determine the dynamic properties and porosity of fibre reinforced UHPC (FRUHPC). Two types of fibres were used: micro steel (MS) and polypropylene (PP) fibres, with three volume fractions of 0.5%, 0.75% and 1.0%. A total of 54 specimens were prepared and tested after 28 days of wet curing for static compression and flexural strengths; dynamic stress and strain; and porosity. The dynamic properties were determined using split Hopkinson pressure bar (SHPB) and porosity by mercury intrusion porosimeter (MIP). The optimum static compressive strength of UHPC is at 0.75% PP fibre inclusion at 150.2 MPa. UHPC with 1.0% MS fibre inclusion exhibits highest flexural strength at 14.2 MPa. PP fibre reinforced UHPC recorded highest value of pore at 15.51% compares to normal UHPC. The ultimate dynamic stresses are between 140 – 160 MPa, ultimate dynamic strains between 0.0006 – 0.002 mm/mm and the ultimate strain rates in the range of 100 s^{-1} and 230 s^{-1}. The highest DIF value is 1.34 for 5% MS fibre reinforced UHPC.

Keywords: *Ultra-high performance concrete; Micro steel fibre; Polypropylene fibre; Static compressive strength, Dynamic properties, Porosity.*

I. Introduction

Ultra-high performance concrete (UHPC) is a new class of concrete that has been developed during recent decades. The first research carried out on UHPC was originated in the mid-1990s. UHPC is a cementations material that contains high quantity of cement, silica fume, and low quantity of water, incorporates large amounts of fibre and high-range water reducing agent. UHPC possesses remarkable ductility, durability and strength properties. UHPC offers very high compressive strength that is > 150 MPa and high tensile strength that is > 8 MPa [1]. The properties of UHPC can be enhanced by (i) further

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reducing the water content in turn reducing the pore diameter, (ii) increase the homogeneity of concrete by removing coarse aggregate and replacing it with finer aggregate and adding pozzolanic materials such as silica fume and (iii) introducing steel fibre in concrete [2].

UHPC has been used on a limited basis in the United Stated since 2000 [1]. Steel fibers are commonly used in UHPC. The high bonding qualities of UHPC enable effective use of fibres toward enhancement of its engineering properties. The high binder content of UHPC also facilitates the dispersion of fibers, which further enhance their reinforcement efficiency [3]. Reference [4] reported that UHPC tends to have very low water content, which is at 0.23 and can achieve sufficient workability and hardened properties through a combination of optimized granular packing with the addition of high-range water-reducing admixtures. The reduction of the water-cement ratio results in a decrease in porosity and refinement of capillary pore in the matrix.

Reference [5] studied the properties of steel and polypropylene (PP) fibres reinforced concrete (FRC) and found that the fresh concrete stiff and difficult to compact. Concrete with shorter fibre has better workability as compared to longer fibre. Steel fibre reinforced concrete (SFRC) properties changes considerably from brittle for plain concrete (PC) to ductile and the mechanical properties of SFRC significantly improves under static and dynamic loadings compared to PC [6]. FRC is able to absorb the energy from loading and transfer the pressure to the fibres until the fibres failed and then transfer the pressure to concrete [7]. The behaviour of concrete under dynamic load is different with the one under static load. Most researches focused on compressive behaviour. Lok et al., 2002 [8] had shown that the dynamic compressive stress increase with addition of fibres in concrete compared to plain concrete. Hao & Hao, 2013 [9] had shown that dynamic stress of spiral steel fibre reinforced UHPC is very sensitive to the strain rate which resulted in higher dynamic compressive stress of spiral steel fibre reinforced UHPC compared to plain UHPC.

Concrete should be design to resist and absorb the energy of manmade and natural forces such as explosion and earthquake. UHPC is a type of concrete with high compressive strength but brittle in its nature. The inclusion of fibre is expected to improve the static and dynamic properties of UHPC. The purpose of this paper is to determine the effect of micro steel (MS) and PP fibres on the static and dynamic properties of UHPC. The porosities of the mixes are also determined to make a link to the changes in the properties.

II. Materials and METHODS

A. Materials

Cement: Ordinary Portland cement ASTM C150 Type 1 with specific gravity of 3.15 was used in this study.

Silica Fume (SF): SF is employed as addition of cement, at 5% by mass of OPC cement.

Aggregate: Natural siliceous sand was used in the concrete mixtures. The size of micro sand is between 100 to 600 µm.

Superplasticiser: A polycarboxylic ether based superplasticiser (BASF) is used to adjust the workability of concrete and as a high range water reducer conforming to ASTM C 494 (type F) with specific gravity of 1.18.

Fibre: Two types of fibres were used to improve the mechanical properties of concrete, MS and PP fibres. The MC fibre is plain and straight with 30 µm in diameter and 18 mm in length. The PP fibre is 12 µm in diameter and 12 mm in length. Figure 1 shows both of the fibres.

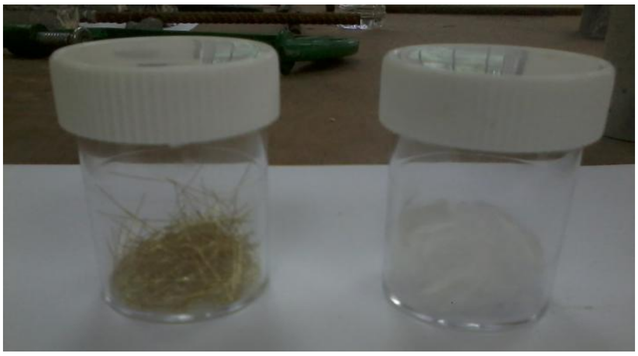


Figure1: Micro steel and polypropylene fibres

B. Methods

1) Details of Mix Proportion and Preparation of Specimens

A 5.6-liter mixer was used in the mixing process of concrete. The mixes incorporated silica fume content of 5 % by mass as an addition of the cement content. A superplasticiser dose of 1 % to 2 % of the cement content by mass was to achieve desired workability of concrete. Two types of fibres (MS and PP) were added to the concrete with three volume fraction of 0.5%, 0.75% and 1.0%. The absolute volume method was used to design the concrete mixes of UHPC [10]. Table 1 shows the details of the concrete mixes. The dry materials were thoroughly mixed for two minutes. The admixture was added to the whole amount of the mixing water that was then slowly added to the dry components. Mixing was continued until the constituents were thoroughly mixed. Flow test was carried out on the fresh concrete to test the workability of concrete. The mixtures cast as specimens using 50 mm^3 standard cube mould for compressive strength, 40 mm × 40 mm × 160 mm prism for flexural strength and 50 mm × 100 mm cylinders for dynamic compression strength. Then the mixtures were compacted using a vibration table in three layers and full compaction was made sure by observing the air bubbles on the surface. After casting, the moulded specimens were covered and left in the casting room at 26 ºC for 24 hours until demoulding. Thereafter, all specimens were cured in the water tank and then tested at room temperature for 28 days of curing.

Table1: Mix design proportion

Sample	Content (%)					
	Cement	Micro Sand	Silica Fume	Fibre	Water	SP
Control	100	40	5	-	20	0.20
MS18F0.50	100	40	5	0.50	20	0.17
MS18F0.75	100	40	5	0.75	20	0.20
MS18F1.00	100	40	5	1.00	20	0.18
PP12F0.50	100	40	5	0.50	20	0.19
PP12F0.75	100	40	5	0.75	20	0..19
PP12F1.00	100	40	5	1.00	20	0.20

2) *Testing Methods*

Static Compressive Strength: Cube specimens were cast to determine the actual compressive strength of each mix at ages of 28 days. The test was conducted according to BS EN 12390-3:2002.

Flexural Strength: The flexural strength of concrete was determined by applying load at the central of prism until failed. The test was conducted according to BS EN 12390-5:2000.

Porosity: The porosity of concrete was determined using mercury intrusion porosimeter test (MIP). MIP has been customarily used to evaluate pore structure in concrete. The sample for this test is taken from the debris of the compressive strength test specimens. The PASCAL 440 MIP was used with the expected measured radius between 1.8 nm to 7500 nm.

Dynamic Properties: The dynamic compressive stress and strain was determined using split Hopkinson pressure bar (SHPB) technique at the pressure of 2 MPa. The SHPB system consists of a launcher tube, a striker bar, a transmission bar, and the energy-absorbing parts. The energy source system contains air compressor and pressure vessel. The measurement system comprises velocity and dynamic strain indicator. The Young's modulus of the projectile, incident and transmission bars is 210 GPa and the UPV of the bars is 5190 m/s. Figure 2 shows the component of a SHPB and Figure 3 shows the close up of the incident bar and the transmission bar with the failed control specimen after the impact test.

In order to make the specimen (a cylindrical specimen of 50 mm × 50 mm∅) contact with the incident and transmitter bars as perfect as possible, specimens contact surfaces were prepared carefully by grinding and smoothing such that the specimen surface are parallel and the roughness on the surface is less than 0.02 mm, based on which it is believed that the error in transmitted stress wave due to the non-perfect contact is negligible. The loading chamber is connected with a nitrogen tank. Two valves are instrumented with

Valve A being connected to the nitrogen tank and Valve B controlling to release the pressure in the chamber. The impact generates pulses and is measured by two strain gauges. The strain signal is recorded using high-speed digital oscilloscope of 10 bit. A program written in MATLAB® is used to analyse the signal pulse wave generated as a result of the impact of the striker bar to the incident and transmission bars using the one-dimensional wave theory.

III. Result and Discussion

A. Static Compressive Strengths

The static compressive strength for each mix is measured at the aged of 28 days and is shown in Table 2. The compressive strength of control is more than 150 MPa which is the targeted compressive strength at the age of 28 days. The results show that 0.75% of PP fibre inclusion is optimum in maintaining the compressive strength value at above 150 MPa with other percentages of inclusion had reduced the strength below 150 MPa. For UHPC with MS fibre inclusion, the strengths were reduced at all percentages of PP fibre inclusion replacement. This is due to the higher length of MS fibre (18 mm compared to 12 mm of PP fibre) which had created higher debonding area with the increase in the fibre-matrix interface [11].

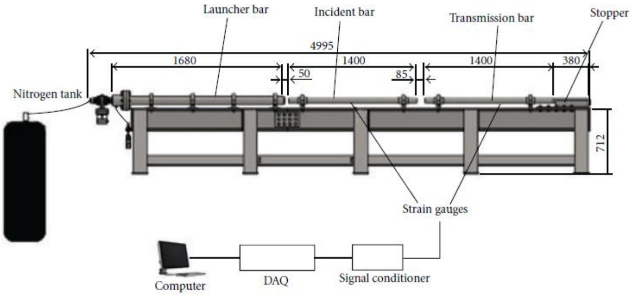


Figure 2: Components of SHPB [6]. All dimensions in mm.

Figure 3: Failed control specimens after dynamic load impact

B. *Flexural Strength*

The flexural strength of the specimens, however, had shown increased in all mixes as shown in Table 2. The flexural strengths of all specimens are more than 8 MPa which is the targeted flexural strength at the age of 28 days. By adding UHPC with PP fibre, the improvement starts from 27.1% at 0.5% and expands to 42.4% at 0.75% and finally to 65.9% at 1.0%. By adding UHPC with MS fibre, the improvement jumps to 41.2% at 0.5% and expands to 58.8% at 0.75% and finally to 67.1% at 1.0%. MS fibre has shown its effectiveness in strengthening the flexural capacity of UHPC. The increase in fibre content results in further increase in flexural tensile strength in UHPC.

C. *Porosity*

The porosity test was conducted only on specimens with 1.0% of fibre which had shown maximum enhancement values of compressive strength. From the result shown in Table 3, the total pores in control UHPC is 12.38 %. PP fibre reinforced UHPC exhibit increased in total pores at 15.51% compared to control. MS fibre reinforced UHPC shows highest value of pore median diameter and highest value of total pore which conform with the compressive strength test result where that mix exhibit the lowest strength among the three. Winslow & Liu, 1990 [12] had shown that larger pore sizes exist in paste at the interfacial zone. The interfacial zone of MC fibre UHPC is higher due to its higher diameter and length compared to PP fibre. The total pore increase with addition of both fibres.

Table 2: Compressive and flexural strength of UHPC

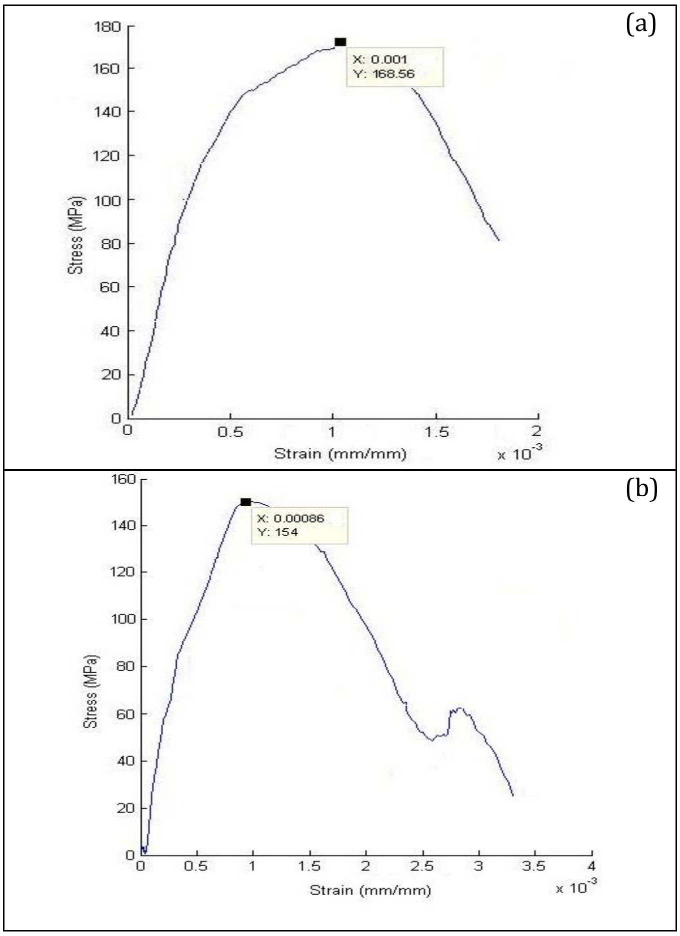
Sample	Compressive strength, 28 days (MPa)	Percentage difference (%)	Flexural strength, 28 days (MPa)	Percentage difference (%)
Control	158.4	-	8.5	-
MS18F0.50	111.9	-29.36	12.0	41.2
MS18F0.75	105.6	-33.33	13.5	58.8
MS18F1.00	128.9	-18.62	14.2	67.1
PP12F0.50	140.4	-11.36	10.8	27.1
PP12F0.75	150.2	-5.18	12.1	42.4
PP12F1.00	140.0	-11.62	14.1	65.9

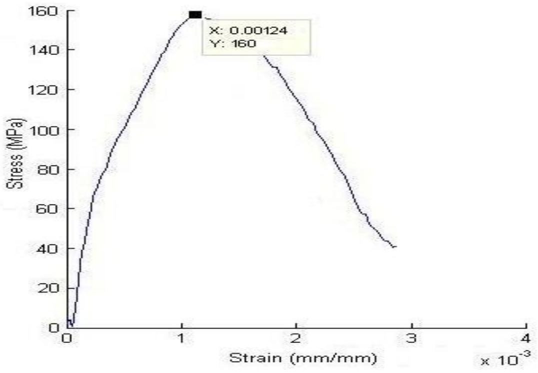
Table 3: Total pores of UHPC

Sample	**Median diameter of pores (μm)**	**Total pores (%)**	**Difference with control (%)**
Control	0.0061	12.38	-
PP12F1.00	0.0110	15.54	20.3
MS18F1.00	0.0152	13.54	8.6

D. Stress-strain Diagram

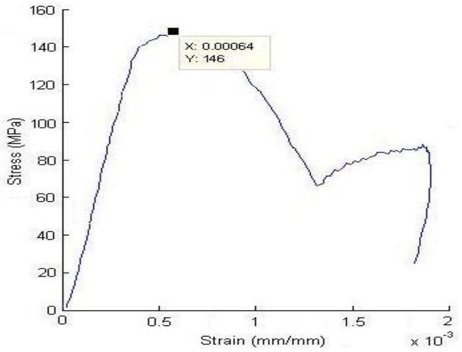
The dynamic stress-strain diagrams of the UHPC are shown in Figure 4. Figure 4 shows FRUHPC post peak load carrying capacity increases compares with control and increases with the increase of fibre content rather than for the increment on the peak stress, which is also reported by Reference [11] for post peak behavior of FRC in flexure. In some specimens, the post peak load carrying capacity has increased after peak load (hardening branch) (Figure 4b) and d)). This behaviour is associated to the occurrence of a higher concentration of fibres in the intermediate layers of the fracture surface. The strain rate, and ultimate dynamic stress and strain are shown in Table 4.




X: 0.00124
Y: 160
Stress (MPa)
0
20
40
60
80
100
120
140
160
0
1
2
3
4
Strain (mm/mm)
x 10^-3

(c)

(d)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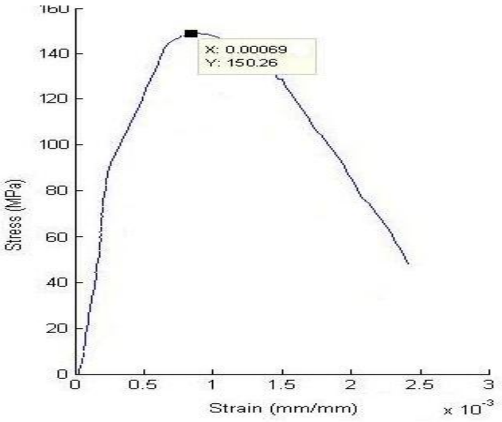
Y: 146
Stress (MPa)
0
20
40
60
80
100
120
140
160
0
0.5
1
1.5
2
Strain (mm/mm)
x 10^-3

(e)


X: 0.00069
Y: 150.26
Stress (MPa)
0
20
40
60
80
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120
140
160
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3
Strain (mm/mm)
x 10^-3

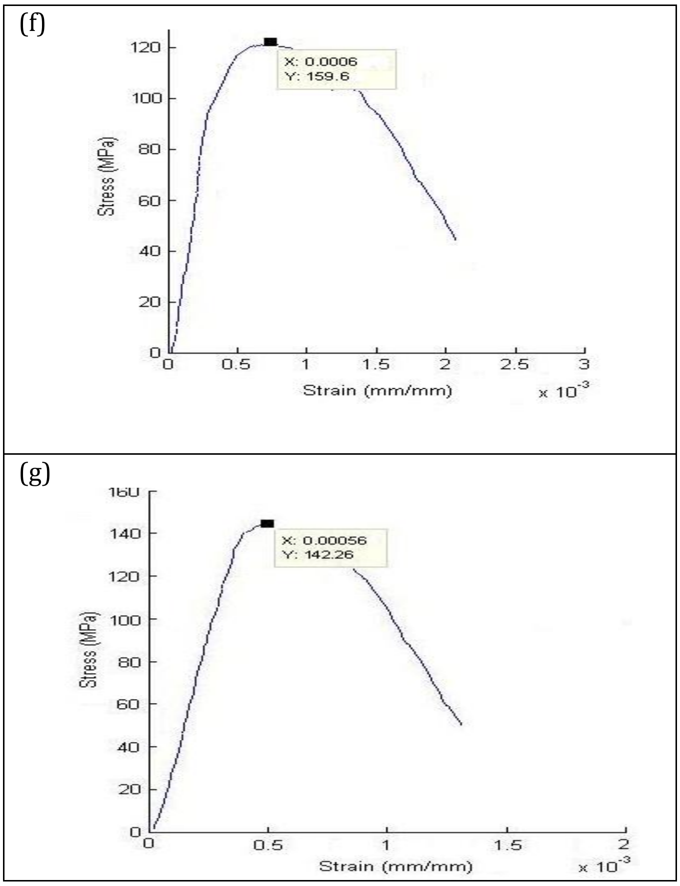

Figure 4: Dynamic stress-strain diagram for a) Control, b) PP12F0.50, c) PP12F0.75, d) PP12F1.00 e) MS18F0.50, f) MS18F0.75 and g) MS18F1.00

The ultimate dynamic stresses are between 140 – 160 MPa, the ultimate dynamic strain between 0.0006 – 0.002 mm/mm at strain rate in the range of 100 s-1 and 230 s-1. The result shows that UHPC which addition of 0.75% PP fibre exhibits highest ultimate dynamic stress among the FRUHPC at 160 MPa and the lowest is UHPC with MS fibre addition of 0.50% at 150.26 MPa. The ultimate strains of FRUHPC also reduced with exception of UHPC with 0.75% MS fibre.

Table 4: Ultimate dynamic stress and strain at different strain rate

Sample	**Strain rate (s^{-1})**	**Ultimate dynamic stress (MPa)**	**Difference with control (%)**	**Ultimate dynamic strain (mm/mm)**	**Difference with control (%)**
Control	125.00	168.56	-	0.00100	-
PP12F0.50	145.35	154.00	-8.64	0.00086	-16.28
PP12F0.75	100.81	160.00	-5.08	0.00124	19.35
PP12F1.00	104.17	146.00	-13.28	0.00086	-16.66
MS18F0.50	181.16	150.26	-10.86	0.00069	-44.93
MS18F0.75	208.33	159.60	-5.32	0.00060	-66.66
MS18F1.00	223.21	142.26	-15.60	0.00069	-44.93

This result is in agreement with Selvi & Thandavamoorthy, 2013 [5], where it can be seen that steel fibre exhibits a hard and resilient system and able to increase the concrete stress before the first crack occur, but at lower strain at failure. Meanwhile, polypropylene fibre is more flexible and ductile which had increased the ultimate dynamic stress and also the strain at the cracking zone.

E. Dynamic increase factor

Table 5 shows the DIF of all specimens and comparison with results from Riisgaard et al. [13]. The highest DIF value is 1.34 with for UHPC with 5% of MS fibre addition. The DIF is influence by the strain rate of loading and the strength of concrete. Dynamic increase factor (DIF)

Table 5: Dynamic increase factor

Sample	Strain rate (s^{-1})	Dynamic stress (MPa)	Static compressive strength (MPa)	Dynamic increase factor (DIF)
Control	125.00	168.56	158.40	1.06
PP12F0.50	145.35	154.00	140.40	1.10
PP12F0.75	100.81	160.00	150.20	1.07
PP12F1.00	104.17	146.00	140.00	1.04
MS18F0.50	181.16	150.26	111.90	1.34
MS18F0.75	208.33	159.60	135.60	1.18
MS18F1.00	223.21	142.26	128.90	1.10
Ref. [13]	81	187	160	1.17
Ref. [13]	187	226	160	1.41
Ref. [13]	267	241	160	1.50

The DIF varies with the strain rate and the content of fibre. One of these parameters needs to be held constant to actually see the variation of DIF with each one. Generally, from Table 5, it can be seen that the DIF decrease with increase of fibre content for both fibre mixes as Riisgaard et al. had shown that increase in strain rate had increased the DIF for a particular mix design.

IV. Conclusion

The current work aimed at investigating the stress-strain relationship and DIF of FRUHPC under dynamic loading. Based on the available result and analysis, the following conclusion could be drawn:

1. Ultra-high performance concrete could be produced utilizing conventional local materials and production techniques with regard to mixing and curing. A 158.40 MPa, 28 days compressive strength was achieved with adequate workability.
2. The highest compressive strength obtained in FRUHPC is at 150.20 MPa for UHPC with 0.75%. PP addition. Overall, the compressive strength decreased when fibres are added to the UHPC.
3. The flexural strengths of fibre reinforced UHPC are increased up to 67.1% compared to the control UHPC. The highest flexural strength was obtained by addition of 1% MS fibre.
4. The porosity of UHPC with PP fibre addition is higher than UHPC with MS fibre addition.
5. The dynamic compressive stresses show that the UHPC with PP fibre addition is more ductile than UHPC with MS addition because the ultimate strains of MSFRUHPC are the lowest among them.
6. The stress-strain relationship of UHPC failure was primarily due to high deformation. The stress corresponding to dynamic loading was found to be up to 1.34 times higher than the static loading.

Acknowledgment

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