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Curing Systems Enhance Strength of Modern Concretes

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Abstract **- The need for modern higher strength and higher performance concretes is rising rapidly, since engineers are seeking superior qualities for their intuitive constructions all over the world. This research study includes adopting different curing regimes to normal, high and ultra-high strength concretes; the curing regimes considered are traditional curing by submerging specimens in ambient room temperatures at 25 ºC, accelerated thermal curing in either warm water at 50 ºC or hot water at 75 ºC, and finally microwave curing at intensities of 300, 500, and 800 Kilowatts for durations of 15 and 25 minutes. Mechanical strength assessment of compression, indirect tension and flexure will be performed on cubes, cylinders and prisms respectively.**

The test results showed that the concrete which contain cement plus silica-fume indicated that heating water curing could further increase the compressive strength of the concretes. The amount of strength gain was from 5 to 10 MPa by using warm water curing at 50 ºC, and was from 10 to 20 MPa by using hot water curing at 75 ºC, also the amount of strength gain was about 5 to 15 MPa by using 15 minutes microwave heating, and was from 10 to 20 MPa by using 25 minutes microwave heating.

Keywords: Accelerated Thermal Curing, Microwave Curing, High Strength Concrete, Ultra-High Strength Concrete.

INTRODUCTION

Fields of precast, pre-stressed and post tensioned concretes have greatly expanded to accommodate the increasing demand for construction of national projects in Egypt. These major projects and their constructions require use of modern concretes that provide superior qualities such as high performance, high strength and occasionally ultra-high strength characteristics [1]. Accordingly, quality control is a vital aspect of both the production and curing of these modern concretes. Acknowledging the high importance of curing concrete for improved strength development, precast elements are factory fabricated and cured in controlled conditions at certain temperatures, under specific pressures, and levels of humidity for definite durations. Such controlled curing regimes which involve elevated temperatures and high levels of humidity for specific periods of time are known as accelerated curing. These curing regimes greatly enhance the hydration process to proceed, hence allowing for the propagation and gain of concrete strength, and in the meantime relieving concrete of strains that may develop due to improper hardening and setting [2-3]. Knowing that curing represents a major and vital factor for concrete strength gain, it is unknown how these superior and dense concretes really benefit from the traditional curing techniques that are practiced on normal grade concretes. The packed density of high and ultra-high strength concretes may prevent curing moisture to reach the unhydrated cement particles at the concrete core, hence rendering curing to be totally inefficient or partially efficient by hindering concrete strength development [4-6]. One of the main properties of concrete that makes pre-casting economically feasible is its ability, under the proper conditions, to gain compressive strength extremely rapidly. The description of the various methods currently available for accelerating the curing of concrete, particularly for precast concrete applications. Two distinct methods for accelerating the curing process exist is the use of physical processes. and the use of admixtures to act as catalysts for the hydration process, resulting in the achievement of high compressive strengths in relatively short periods of time. Typical physical processes used to accelerate the curing process are generally combinations of the following: increases in curing temperature, introduction of moisture to curing environment. The use of admixtures in order to accelerate the curing process can be further subdivided into the use of mineral and chemical admixtures. Calcium Chloride has proven to be an extremely effective accelerator; however, due to corrosion concerns, its use in concrete with embedded metal is not recommended. The most common mineral admixture used as an accelerator is micro silica, or silica fume. Some chemical admixtures, such as high-range water reducers (HRWR), or superplasticizers, have been used as indirect accelerators, primarily due to their ability to reduce the water demand for a given mix, Brent Vollenweider [4]. Microwave is one of the most popular energy sources used to heat dielectric materials for various industrial processes. Due to the advantages of volumetric heating, MWs can be implemented in a reasonable way to improve the rate of concrete strength development. Microwave heating, which is based on internal energy dissipation associated with excitation of molecular dipoles in electromagnetic fields, allows faster and more uniform heating which implies that short process time is sufficient to provide high early strength, Natt Makul [5].

1. EXPERIMENTAL PROGRAM

This study includes the production of three different concrete grades; normal strength concrete (NSC), high strength concrete (HSC) and ultra-high strength concrete (UHSC). Specimens of each grade will be subjected to the following different curing regimes:

- *Conventional curing*
  1) Ambient water curing
  Specimens are submerged in ambient temperature waters at 25 ºC till the day of testing.
- *Accelerated curing*
  2) Warm Water curing
  Specimens are submerged in warm temperature waters at 50 ºC for seven days and then submerged in ambient temperature waters at 25 ºC till the day of testing.
  3) Hot Water curing
  Specimens are submerged in warm temperature waters at 75 ºC for seven days and then submerged in ambient temperature waters at 25 ºC till the day of testing.
- *Microwave curing*
  Microwave curing includes six different cases where specimens will subjected to three different micro wave intensity levels where each level will be adopted for two different durations.
  4) Low intensity 300 Watts
  A) Duration of 15 minutes B) Duration of 25 min
  5) Moderate intensity 500 Watts
  A) Duration of 15 minutes B) Duration of 25 min
  6) High intensity 800 Watts
  A) Duration of 15 minutes B) Duration of 25 min

After which, specimens of the three concrete grades will be assessed for strength by testing cubes in compression, cylinders in indirect tension and prisms in flexure (Fig. 1).

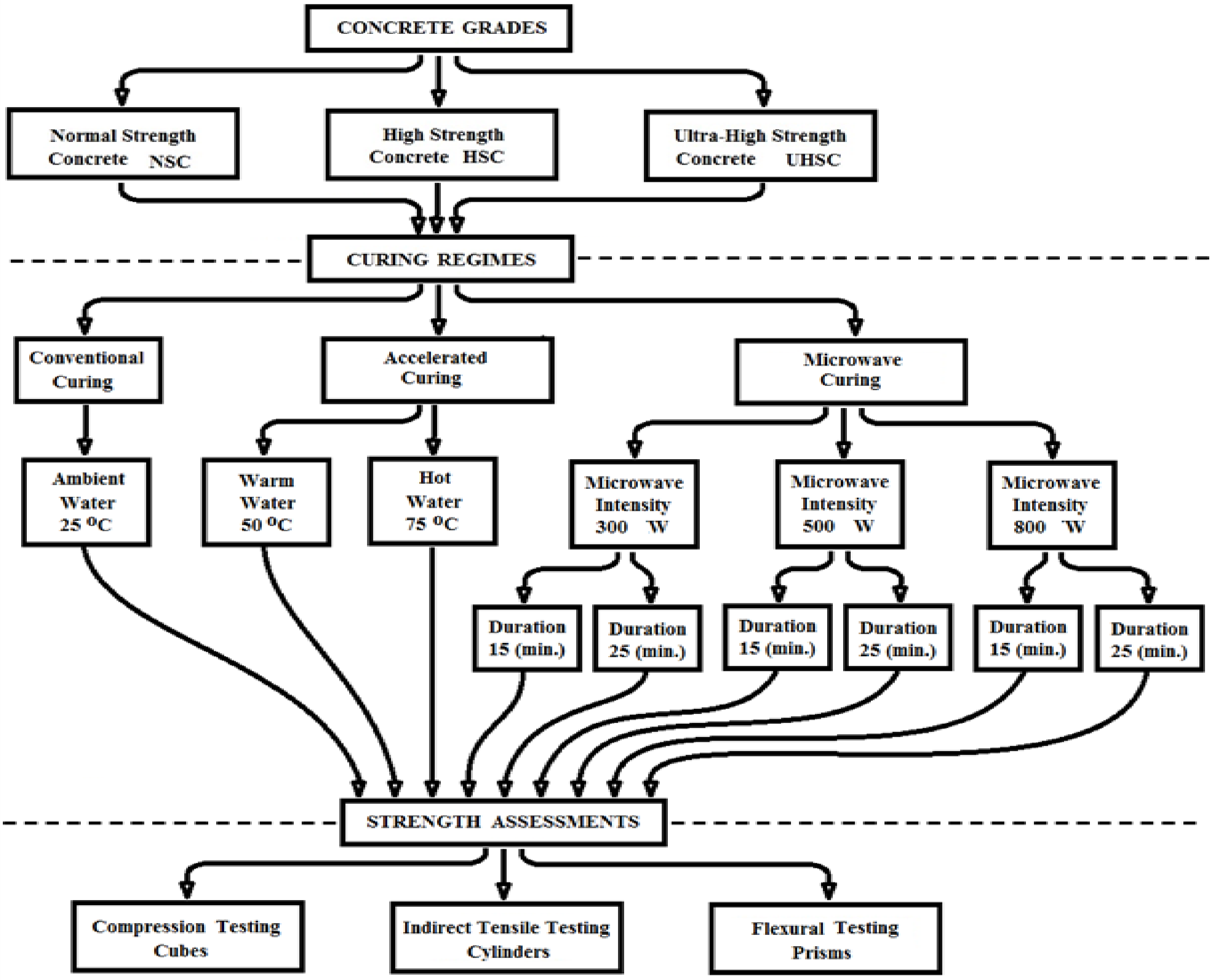

Fig 1: Experimental Program Flow Chart

2. MATERIALS AND PROPERTIES

Various materials were adopted for the different modern concretes considered according to their grades (NSC, HSC, and UHSC). An extensive pilot study was performed, during which materials were altered and mixes were designed, executed and tested for strength evaluation in order to reach an applicable concrete possessing suitable fresh and hardened characteristics.

Cement

Ordinary Portland cement produced by the Sina cement company (grade 52.5N), which complies with Specifications and standards of Cement type I, was used for all three concretes NSC, HSC, and UHSC

Coarse aggregates

Two types of coarse aggregate were used Dolomite and Basalt, where the Dolomite was of two sizes. Dolomite size #1 (passing sieve 9.51 mm and retained on sieve 2.36 mm) and size #2 (passing sieve 19.0 mm and retained on sieve 9.51 mm), but the Basalt was of size #1 (passing sieve 9.51 mm and retained on sieve 1.18 mm) only as illustrated (Fig. 2). A mixture of both sizes of Dolomite was adopted for the normal strength concrete NSC, while Dolomite of size #1 only was adopted for high strength concrete HSC and Basalt of size #1 was adopted for ultra-high strength concrete UHSC.

Fine aggregate

The fine aggregate used for the three concretes consisted of clean, dry, medium fine, siliceous sand of a fineness modulus of 2.3 with a sieve analysis illustrated (Fig. 2).

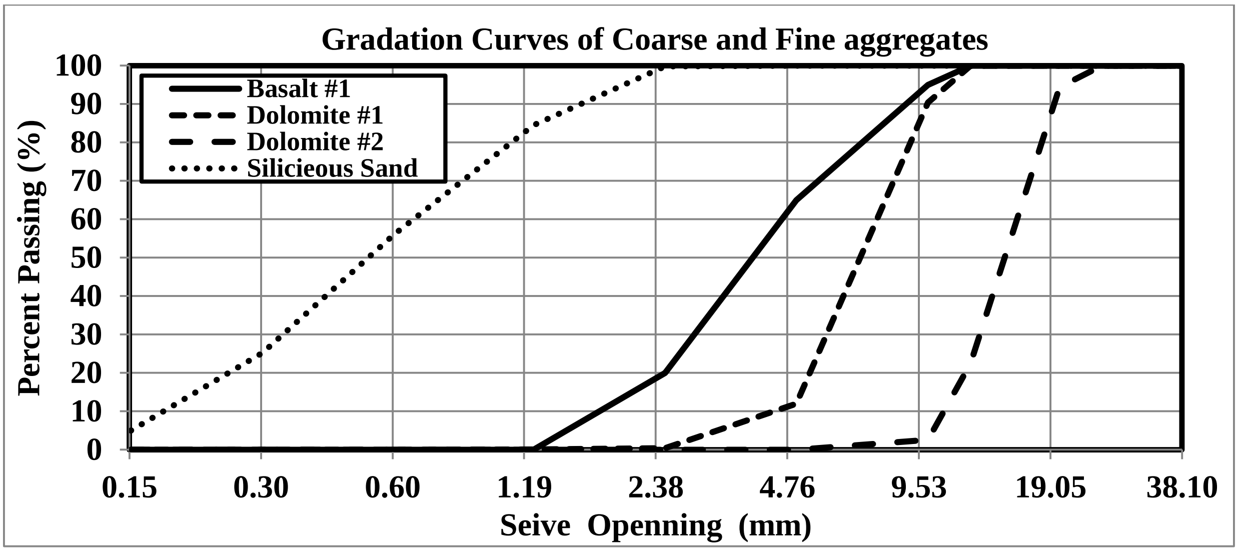

Fig 2: Particle Size Distribution of Coarse and Fine Aggregates

Silica Fume

The mineral admixture silica fume, considered a supplementary cementing material, was used in addition to the cement for the HSC and UHSC mixes in doses 14% and 28% respectively. The silica fume used, a product of Sika Company, is a grey colored, new generation of extremely fine 0.1μm latently reactive particles of silicon dioxide having a bulk density of 300 Kg/m^3. Which provides excellent workability, promotes high early strength, and reduces both liquid and gas permeability [8].

High Range Water Reducer

The chemical admixture used is a product of Sika Company (known as Sikament NN) which is a dark brown, Naphthalene Formaldehyde Sulphonate base superplasticizer liquid possessing a specific gravity of 1.2 Kg/lit with an 8±1 PH value. This high range water reducer is used for both the HSC and UHSC mixes at doses of 3.1% and 4.4% respectively.

3. CONCRETE MIX DESIGNS

An intensive pilot study was carried out where many refinements of several trials were performed in order to reach mix designs that proved to be applicable in practice (Table 1). The normal strength NSC, high strength HSC, and ultra-high strength UHSC were designed to achieve a 28 day compressive strength of 400, 750, and 1200 Kg/cm^2 respectively.

Table 1: Mix design of Normal, High and Ultra-High Strength Concretes

Constituent	Concrete Grades		
	Normal Strength NSC (Kg/m^3)	High Strength HSC (Kg/m^3)	Ultra-High Strength UHSC (Kg/m^3)
Cement	400	500	700
Silica Fume (s/c)	----	70 (14%)	196 (28%)
Basalt #1	----	----	960
Dolomite #1	780	1170	----
Dolomite #2	370	----	----
Siliceous Sand	700	550	410
Water (w/c)	208 (0.52)	150 (0.30)	168 (0.24)
Superplasticizer	----	15.5	31
Concrete Weight	2458	2455.5	2465

4. CURING REGIMES

Specimens will be cured using three regimes, the first is considered a reference where curing is performed by submergence in ambient waters of 25°C, the second is accelerated curing by submergence in warm waters of 50°C and hot waters of 75°C till the day of testing in case of three days age, or seven days then submerged in ambient waters of 25°C for 28 days of age and beyond, where elevated temperatures were controlled using a thermostat immersed in the water tanks. The third regime is microwave curing which was altered in intensity at 300, 500 and 800 Watts where for each intensity the duration is changed from15 to 25 minutes (Fig. 1). After demolding the specimens, micro wave curing procedure included immersing the specimen in a glass containing water and adjusting the microwave to the designated wattage for the specified duration, and then specimens were left to cool down before being submerged in ambient temperature waters 25°C till the day of testing.

5. STRENGTH ASSESSMENTS

A total of 240 cube of 10 cm side length were tested at 3, 7, 28 and 90 days of age, while 189 cylinder specimens 7.5 cm in diameter and 15 cm in height, while 27 prism specimens 10 cm in width and height and 50 cm in length were tested at 3, 7 and 28 days of age. Cubes were tested for compressive strength, cylinders were tested for indirect tensile strength and prisms were tested for flexural strength [9].

Compressive Strength Test

Each cube specimen is weighed dry and its loading surface measured in two perpendicular directions (for area A calculations) then centered under the loading plates, where the load is lowered slowly at a rate of 40 Kg/cm^2 per second till failure. The maximum compressive load P_{max} causing failure is recorded and the compressive strength is calculated by

$$f_{cu} = \frac{P_{max}}{A}$$

Indirect Tensile Strength

Each cylinder is weighed dry and its diameter D and length L is measured accurately then placed on its side in contact with two strips of plywood under the loading drums and loaded slowly at a rate of 40 Kg/cm^2 per second till failure. The maximum load P_{max} causing splitting of the cylinder in two halves is recorded and the indirect tensile strength is calculated by

$$f_t = \frac{2.P_{max}}{\pi.D.L}$$

Flexural Strength

Each prism is marked with a support span L which is to be subjected to three point loading. The prism is placed on the supports and the loading roller is adjusted to the middle of the support span and centered on top of the specimen. Specimens are loaded slowly and gradually at a rate of 40 Kg/cm^2 per second till fracture occurs. The maximum load P_{max} causing the fracture is recorded along with the section moment of inertia I and extreme fiber height y, then the Maximum moment M_{max} and the bending stress f_b is calculated by

$$f_b = \frac{M_{max}}{I}.y \qquad \text{where} \qquad M_{max} = \frac{P_{max}}{2}.\frac{L}{2}$$

6. RESULTS AND DISCUSSION

6.1 Traditional, Thermal and Microwave Curing effects on Compressive Strength

Tables (2) summarizes the compressive strength results for normal concrete (N.S.C), high and ultra-high strength concrete (H.S.C and UHSC) under different curing systems at ages 3, 7, 28 and 90 day.

Table 2: Compressive strength of different curing regimes for different concretes

Concrete Grade		Normal Strength Concrete NSC (MPa)				High Strength Concrete HSC (MPa)				Ultra-High Strength Concrete UHSC (MPa)			
Age		3	7	28	90	3	7	28	90	3	7	28	90
Traditional Curing													
Ambient Temp 25 °C		22.9	27.7	43.2	45.2	50.7	57.5	75.5	78.2	68	87.8	109.3	120.9
Accelerated Curing													
Warm Temp 50 °C		23.6	28.9	40.8	45.7	57.8	66.3	76.8	80.9	72.7	92.1	114.8	125.8
Hot Temp 75 °C		24.8	30.2	41.5	45.2	61.8	76.8	85	88.7	77.5	100.3	120.5	128.2
Microwave Curing													
Intensity	Duration												
300 Watts	15 min	24.4	30.1	40.8	41.0	54.1	61.7	72.4	78.1	68.3	88.2	111.4	121.8
	25 min	25.0	31.3	43.3	44.5	58.6	70.9	78.6	82.5	73.9	94.4	112.9	122.9
500 Watts	15 min	24.1	31.4	39.3	40.5	59.7	68.8	79.2	82.5	72.9	93.3	116.9	122.5
	25 min	25.9	32.9	41.3	45.5	60.2	76.5	81.6	84.6	74.5	98.9	120.9	123.9
800 Watts	15 min	26.2	31.5	39.3	41.5	61.2	73.4	82.9	85.3	74.5	97.4	121.5	125.4
	25 min	23.2	29.6	41.8	42.5	62.2	77.0	84.7	88.5	77.1	104.5	124.5	129.8

Effect of Thermal Curing on Compressive strength of Concretes

The results imply that temperature accelerated curing improves the compressive strength of NSC at early ages 3 and 7 days with minor loss at 28 days but eventually reaching its strength at later ages 90 days. Whereas temperature accelerated curing considerably improves compressive strength of HSC at early ages 3, 7 and 28 days with minor loss at later ages 90 days. Also temperature accelerated curing considerably improves compressive strength of UHSC at early ages 3, 7, 28 and 90 days as in (Fig. 3 and Fig. 4). This slight improvement of compressive strength at early ages of 3 and 7 days for NSC is attribute to the elevated temperatures that enhance the hydration process and drive it forward but since the cement content is limited in this mix to 400 kg/m^3 (with a water cement ratio of 0.52) subsequently the amounts of tricalcium (C_3S) and dicalcium (C_2S) silicates are also limited, therefore the final amount of hydrated cement reaches a threshold level that cannot be exceeded. This threshold level is dictated by the amount of calcium silicate hydrate gel $C_3S_2H_8$ which is responsible for the bond between the cement paste and aggregate particles which states the final strength of concrete.

Hydration Process occurs at two levels for normal strength concretes

1) Hydration of Tricalcium Silicate (responsible for the early strength gain)

$$2C_3S \;+\; 11H \xrightarrow{\Delta} C_3S_2H_8 \;+\; 3CH$$

Tricalcium Silicate — Calcium Silicate Hydrate — Calcium Hydroxide

2) Hydration of Dicalcium Silicate (responsible for the later strength gain)

$$2C_2S \;+\; 9H \xrightarrow{\Delta} C_3S_2H_8 \;+\; CH$$

Dicalcium Silicate — CalciumSilicateHydrate — Calcium Hydroxide

On the contrary a considerable improvement occurs in the HSC while superior improvement occurs in the UHSC due to the higher cement contents 500 (w/c of 0.3) for the HSC mix and 700 (w/c of 0.24) for the UHSC mix. Consequently HSC and UHSC possess higher amounts of tricalcium (C_3S) and dicalcium (C_2S) silicates therefore the final amount of hydrated cement particles that are in the form of calcium silicate hydrate $C_3S_2H_8$ reaches much higher threshold levels in both HSC and UHSC concretes.

Supplementary Hydration Process of HSC and UHSC mixes

The cement is composed mainly of both tricalcium (C_3S) and dicalcium (C_2S) silicates which react with the hydrogen of the water producing the calcium silicate hydrate $C_3S_2H_8$ that is the bonding agent that bonds the aggregate particles together in a rock like concrete matrix. Their hydration generates heat and also produces calcium hydroxide (CH) where it is worth noting that tricalcium silicate produces three times as much calcium hydroxide (CH) produced by dicalcium silicate. This surplus of calcium hydroxide in the presence of additional silica leads to a pozzolanic reaction that amends the strength development and its gain.

Pozzolanic Reaction

$$3CH \;+\; 5H \;+\; 2S \xrightarrow{\Delta} C_3S_2H_8$$

Calcium Hydroxide — Additional Silica — Additional Calcium Silicate Hydrate

This residual calcium hydrate reacts with any other additional source of silica (silica fume, fly ash, blast furnace slag, …etc.) to produce additional calcium silicate hydrate gel that further enhances the bond and resides in the pores densifying the concrete hence achieving higher strengths in cases of high strength and ultra-high strength concretes where this reaction is known as the pozzolanic reaction.

Effect of Microwave duration and intensity on the compressive strength

For NSC microwave proves to be beneficial at the early ages (3 and 7 days) although the final strength does not reach that reached by the reference concrete cured traditionally in ambient temperature 25ºC waters. While for HSC microwave curing is much more helpful in the early ages of concrete than the NSC but the final strength reaches levels that are slightly lower than that reached by traditional curing. But for UHSC the microwave curing is superiorly beneficiate for ages 3, 7, and 28 days and the strength at 90 days exceeds that of the traditionally cured concretes especially for longer durations (25 min) and higher intensities (800 Watts). Obviously increasing both the intensity from 300 to 800 Watts and the duration from 15 to 25 minutes assists in further hydration of cement particles.

Effect of Silica Fume on Microwave Micro-cracking and concrete strengths

Presence of an additional source of silica in the concrete mix (namely silica fume) assists the process of autogenous healing of the microwave produced micro-cracks in the concrete matrix Here the silica fume reacts with the calcium hydroxides hydrates (CH) (resulting from the hydration process) forming additional calcium silicate hydrates (CSH) which reside in the micro-cracks regenerating the bond. This explains the better performance of high strength (HSC) and the superior performance of ultra-high strength (UHSC) concrete mixes as compared to the normal strength (NSC) concrete mix. Considering the normal strength concrete mix which possesses a 400 kg/m^3 cement content accordingly has a limited hydration potential. The calcium hydroxide produced as a result of the hydration process does not proceed to form additional calcium silicate hydrate (CSH) due to the absence of additional silica (no silica is added for NSC mix). The high water cement ratio of 0.52 hence the abundance of water in the mix allows for more cracking due to greater water molecular movements caused by microwaves and as a result no autogenous healing of the micro-cracks occurs. On the contrary the HSC possesses a cement content of 500 kg/m^3 cement content which has a higher hydration potential and threshold and its low water content (w/c of

0.3) is prone to less microwave induced microcracking. In addition to the ordinary hydrating process the residual calcium hydroxide hydrates react and combine with the additional silica fume (14%) to produce supplementary calcium silicate hydrate which resides in the micro cracks and regenerates the bond causing autogenous heeling of concrete. Similarly the HSC possesses a cement content of 700 kg/m^3 cement content which has a much higher hydration potential and threshold and its low water content (w/c of 0.24) is prone to less microwave induced micro cracking. Also the residual calcium hydroxide hydrates react and combine with the additional silica fume (28%) to produce supplementary calcium silicate hydrate which resides in the micro cracks and regenerates the bond causing autogenous heeling of concrete.

6.2 Traditional, Thermal and Microwave Curing effects on Tensile Strength

Tables (3) summarizes the splitting strength results for normal concrete (N.S.C), high and ultra-high strength concretes (H.S.C and UHSC) under different curing systems at ages 3, 7 and 28 days.

Table (3): Tensile strength of different curing regimes for different concretes

Concrete Grade		Normal Strength Concrete NSC (MPa)			High Strength Concrete HSC (MPa)			Ultra-High Strength Concrete UHSC (MPa)		
Age		3	7	28	3	7	28	3	7	28
Traditional Curing										
Ambient Temp 25 °C		3.14	4.25	5.93	5.56	6.93	7.99	7.01	8.24	10.86
Accelerated Curing										
Warm Temp 50 °C		3.60	4.36	5.66	6.16	7.40	8.1	7.74	8.84	11.38
Hot Temp 75 °C		3.61	4.45	5.56	7.47	8.14	9.01	8.49	9.88	12.13
Microwave Curing										
Intensity	Duration									
300 Watts	15 min	3.03	3.79	5.66	5.04	5.94	8.05	6.74	8.05	10.54
	25 min	3.32	3.98	5.78	6.90	7.67	8.19	7.82	8.61	10.43
500 Watts	15 min	3.18	3.97	5.89	5.58	6.80	7.93	7.59	8.27	10.48
	25 min	3.61	4.09	6.12	7.08	8.43	8.61	8.44	9.29	11.11
800 Watts	15 min	3.49	3.71	6.00	7.14	8.27	8.78	8.39	8.95	10.94
	25 min	3.66	4.52	5.66	7.48	9.18	9.35	8.73	9.63	11.33

Tensile strength results of reference traditional curing at 25°C, accelerated thermal curing at 50°C and 75°C and microwave curing for NSC, HSC and UHSC are presented in (Fig. 5 and Fig. 6).

6.3 Traditional, Thermal and Microwave Curing effects on Flexural Strength

Tables (4) summarizes the flexural strength results for normal concrete (N.S.C), high and ultra-high strength concretes (H.S.C and UHSC) under different curing systems at ages 3, 7 and 28 days.

Table (4): Flexural strength of different curing regimes for different concretes

Concrete Grade	Normal Strength Concrete NSC (MPa)			High Strength Concrete HSC (MPa)			Ultra-High Strength Concrete UHSC (MPa)		
Age	3	7	28	3	7	28	3	7	28
Traditional Curing									
Ambient Temp 25 °C	4.14	4.56	5.28	6.78	7.38	9.36	8.52	9.24	11.52
Accelerated Curing									
Warm Temp 50 °C	3.54	4.26	5.22	8.52	9.36	10.46	9.36	10.32	11.76
Hot Temp 75 °C	3.90	4.74	5.26	9.36	11.4	11.5	10.56	13.32	13.56

Flexural strength results of reference traditional curing at 25ºC, accelerated thermal curing at 50ºC and 75ºC and microwave curing for NSC, HSC and UHSC are presented in (Fig. 7).

CONCLUSIONS

1) Accelerated thermal curing at 50ºC and 75ºC is beneficiate for achieving early strength for normal strength concretes but the hydration potential threshold cannot be exceeded.
2) Accelerated thermal curing at 50ºC and 75ºC is beneficiate for achieving higher early and later strength for high and ultra-high strength concretes where the hydration potential threshold is much higher and the additional silica further reacts with the calcium hydroxide hydrates hence elevating the hydration potential threshold to a higher level.
3) Microwave curing is not recommended for normal strength concretes of low cement content and high water cement ratio due to the extensive micro cracking that may occur.
4) Microwave curing proves to be very beneficiate for both high strength and ultrahigh strength concretes of high cement contents low water cement ratios and additional silica of any form.
5) Microwave curing is beneficiate for high and ultra-high strength concretes where the uniform heating drives the hydration process forward hence producing more residual calcium hydroxide hydrates that react with the additional silica producing more calcium silicate hydrates that reside in micro cracks regenerating the bond leading to autogenous heeling.
6) Improvement of the compressive strength is less in percentage (but more in value) than that of tensile and flexural strength due to the nature of the test where compression loads bear on the concrete till the final stages at which the cement bond breaks, while tensile and flexure loads are directly applied to the cement bond till it breaks.

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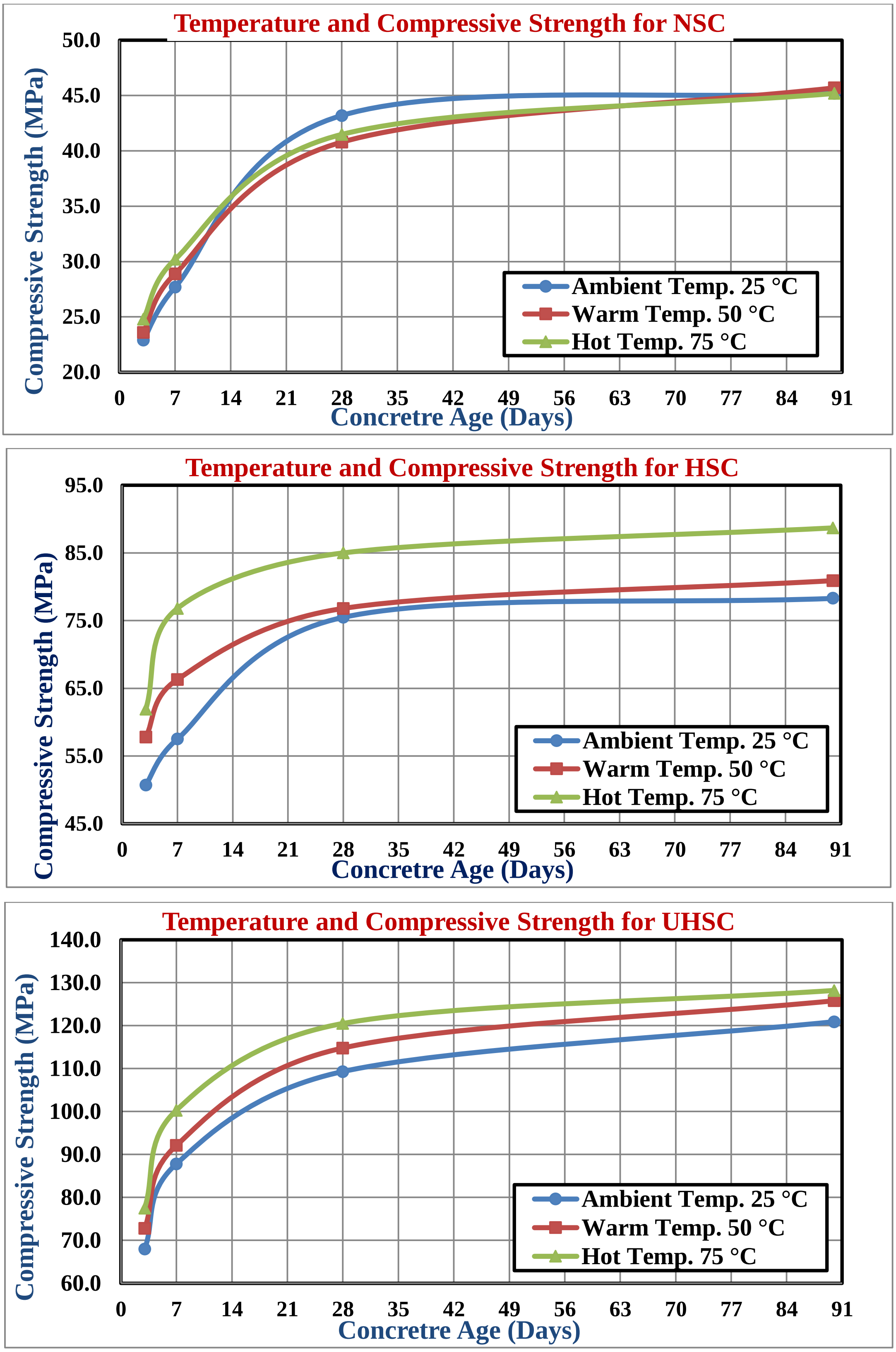

Fig 3 : Compressive Strength of Concrete Grades under Traditional & Accelerated Curing

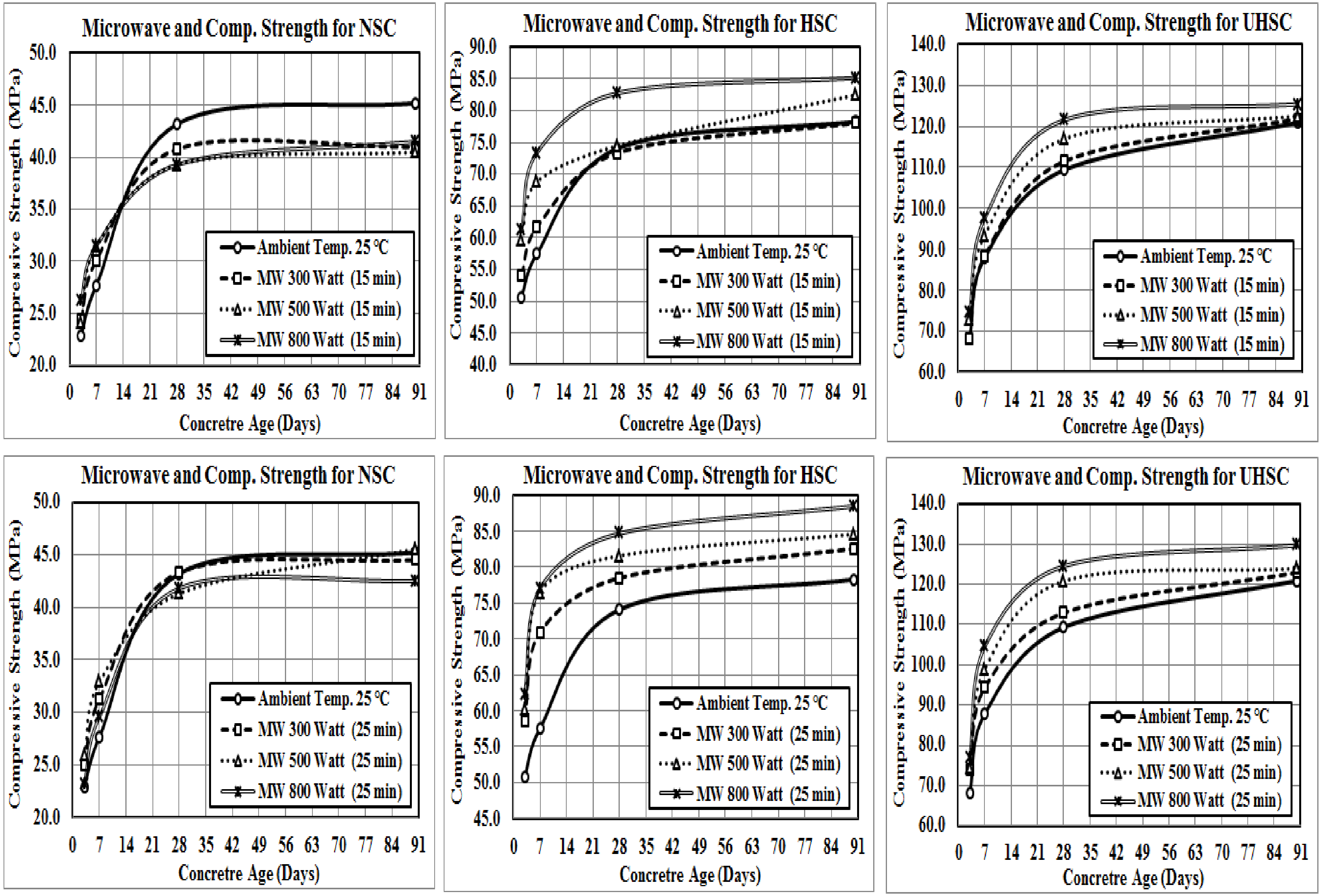

Fig 4 : Compressive Strength of Concrete Grades under Traditional & Microwave Curing (Intensities and Durations)

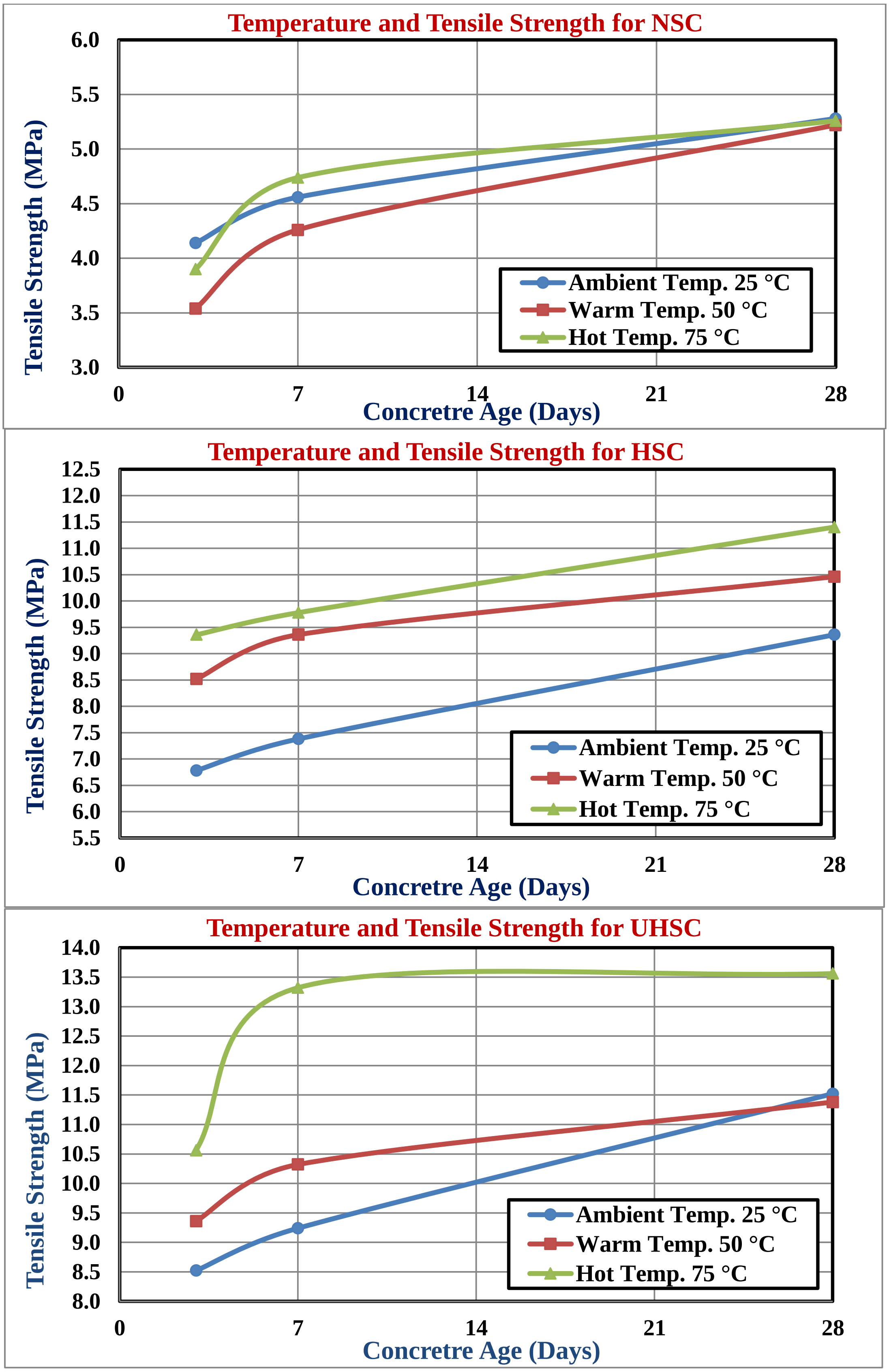

Fig 5 : Tensile Strength of Concrete Grades under Traditional & Accelerated Curing

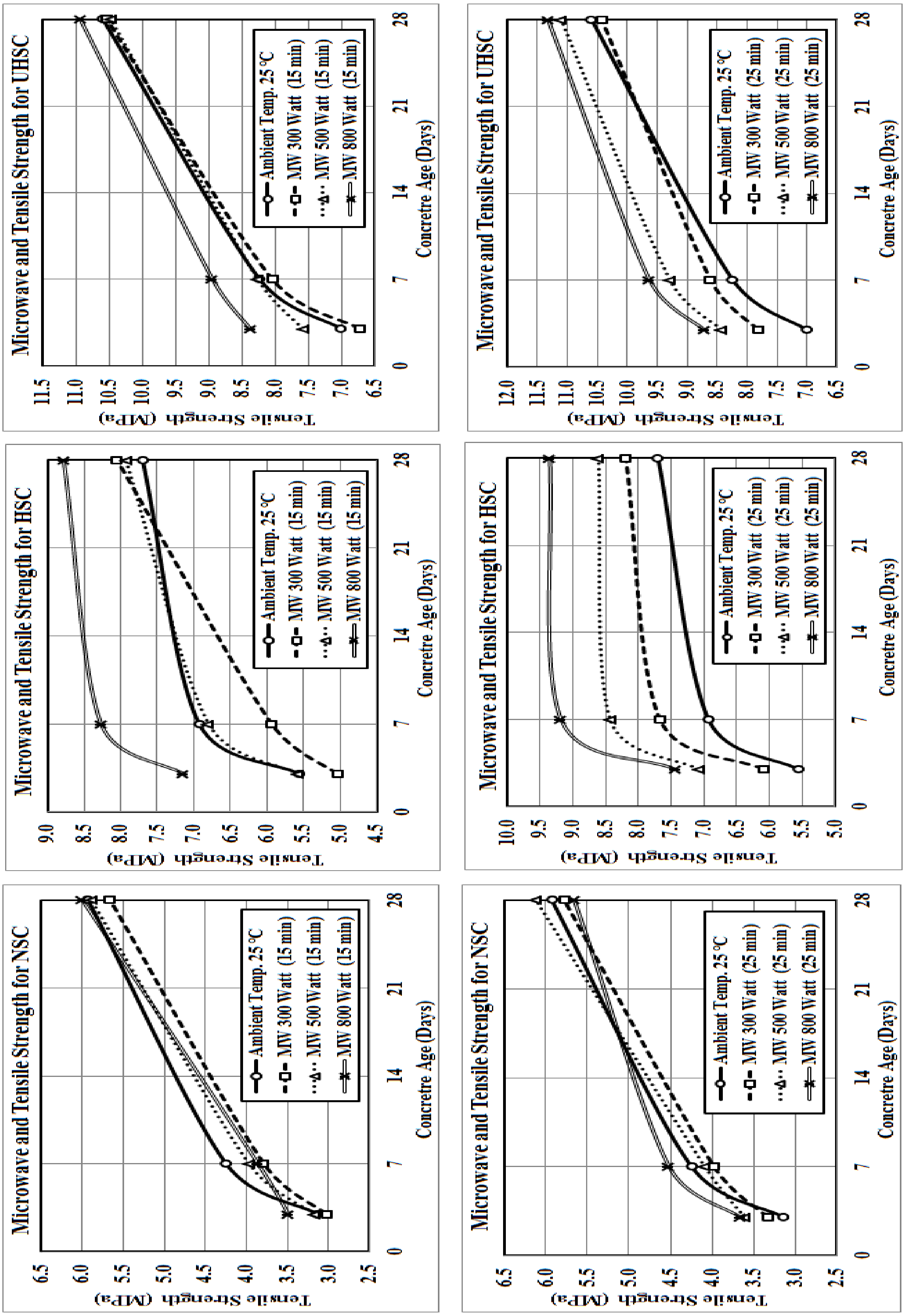

Fig 6 : Tensile Strength of Concrete Grades under Traditional & Microwave Curing (Intensities and Durations)

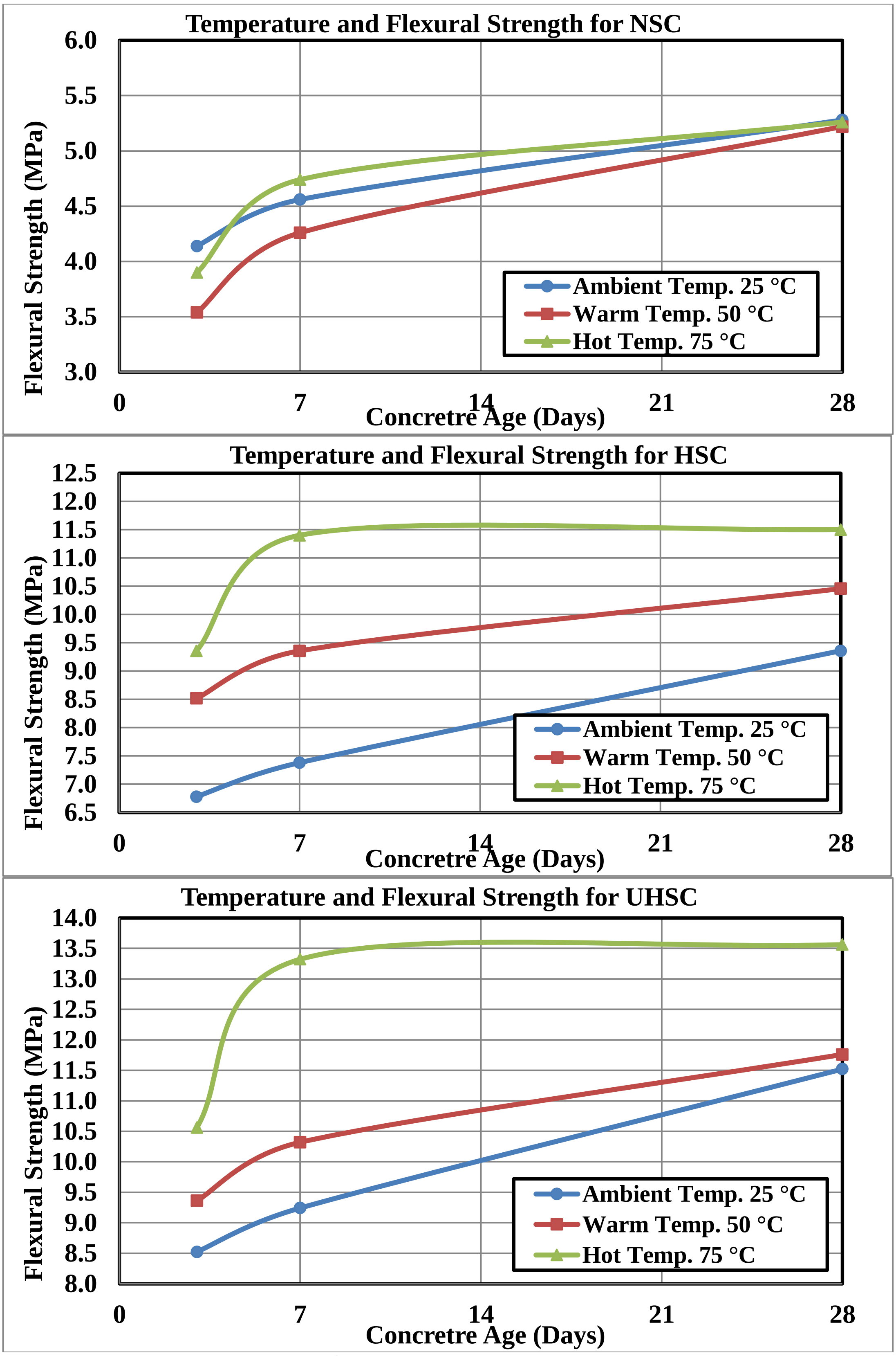

Fig7 : Flexural Strength of Concrete Grades under Traditional & Accelerated Curing