Effect of Fiber Addition, Heat Treatment, and Preset Pressure on Mechanical Properties of Ultra-High-Strength Mortars

K. V. Harish, J. K. Dattatreya, and M. Neelamegam

In this study, efforts were undertaken to produce ultra-high-strength mortars (UHSM) from conventionally available materials. Selection of mixtures and optimization of mixtures were achieved by adopting the basic principles of UHSM and through trial studies. A preliminary investigation was carried out to assess the effects of different curing regimes on the strength development of UHSM. Effects of fiber addition, heat treatment, and preset pressure on the rate of strength development of UHSM mixtures were individually assessed to better understand their benefits in the production of UHSM. Mechanical properties of the heat-treated UHSM were then investigated to determine the performance of the UHSM developed from conventional materials. Results from this study suggested that for the production of UHSM, a multiple curing regime was best suited and was then used for further studies. Data on strength development indicated that heat treatment increased the strengths by 57% to 75%. With application of preset pressure, the compressive strengths of UHSM were increased significantly by 15% to 18%. The optimum quantity of fibers to produce UHSM was found to be 2% to 3%. Effectiveness of fibers in increasing the strength of UHSM was found to be higher for heat-cured specimens than for normal water-cured specimens. The maximum target strengths obtained from the UHSM were 194 MPa, 24 MPa, and 31 MPa for compression, split tension, and flexure, respectively. The UHSM also showed improved energy absorption and toughness characteristics, especially at higher-fiber dosages.

Ultra-high-strength mortars (UHSM), or reactive powder concretes, are a new generation of advanced cementitious composites possessing superior mechanical properties over conventional cement-based materials. The compressive and flexural strengths of these mortars vary from 170 to 230 MPa and from 25 to 60 MPa, respectively, whereas their fracture energies and elastic modulus vary from 15,000 to 40,000 J/m^2 and 54 to 60 GPa, respectively (*1–5*). The basic principles used in the production of these UHSM include homogeneity enhancement, optimization of the granular mixture, selection of granular components, application of pressure, microstructure enhancement through heat curing, and ductility enhancement through the incorporation of fibers (*1, 2*). These principles are achieved through the careful selection of materials, precise gradation of all ingredients in the mixture to yield maximum density, use of very low water–cementitious material (w/cm) ratio (< 0.2), and mixture optimization processes (*2*).

The high target strengths are derived from the pozzolanic reactions of highly refined silica fume, reactivity of quartz at higher temperatures, and use of microsteel fibers (*2, 6–11*). These, in turn, depend on the heat treatment technique (*2, 7, 8, 11*). Heat treatment is considered the classic approach for altering the microstructural properties of cement-based materials and improving their strengths, thereby becoming a requisite for the production of UHSM (*8*). Various techniques, such as hot-water curing (HWC), steam curing, hot-air curing (HAC), and autoclaving, have been used with the optimized mixture to increase its strength from high to ultra-high levels (*2, 4, 9, 10*). Most researchers have investigated single heat treatment techniques, testing various curing regimes to obtain different orders of compressive strengths. The most commonly used include temperatures in the order of 60°C, 90°C, 160°C, 200°C, and 250°C, the result indicating that different compounds are formed at different temperatures (*12*). For example, at temperatures of approximately 200°C, the specimens show residual expansion without cracking resulting from formation of low-density tobermorite. Because the density of the calcium silica hydrates (C-S-H) in reactive powder concrete is high, this production of tobermorite results in improved filling of vacant spaces and, hence, a low porosity threshold. At temperatures above 200°C, compounds such as truscottite, gyrolite, xonotlite, and hillebrandite are formed, depending on the calcium oxide to silicon dioxide ($CaO–SiO_2$) ratio (*4, 12*). Of these compounds, xonotlite, identified as the most important, has been found to contain fewer molecules (C:H = 6) than other C-S-H (C:H = 1). A slight increase in porosity is seen in specimens cured at temperatures up to 250°C, whereas a substantial increase in porosity has been seen at temperatures beyond 250°C (*12*).

A second method of increasing the compressive strength of concrete is using compaction techniques on the wet mixtures. For more than 20 years, various compaction techniques—for example, hand compaction, rollers, and external and internal vibrators—have been used to increase the density of concrete, to remove entrapped air voids, and to remove excess water from concrete mixtures, all of which have resulted in improved mechanical properties. For concretes with a w/cm ratio of 0.3 to 0.4, the amount of water available for workability is not enough since most of it is used for cement hydration. The compaction of such concretes is often achieved by using internal vibrators or by adding appropriate superplasticizers to

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Transportation Research Record: Journal of the Transportation Research Board, No. 2240, Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 59–69.
DOI: 10.3141/2240-09

the mixture. For cementitious composites such as UHSM, with a w/cm less than 0.2, the wet mixture is compressed by applying a preset pressure to eliminate weak links such as air voids, to reduce its porosity, increase its density, and obtain a well-compacted mixture. This compaction technique is used to minimize problems in mixtures containing the higher quantity of fibers associated with fiber balling. Although research on the use of preset pressure to increase the compressive strength of UHSM has been found to improve the microstructure of the composite (*2, 4, 12, 13*), its effect on the wet UHSM mixtures has not yet been fully studied.

The energy absorption properties of concretes, such as toughness, fracture energy, and impact resistance, can be enhanced by incorporating steel fibers into the concrete mixture. The quantity, aspect ratio, size, shape, and ultimate tensile strength of these fibers are critical factors affecting these properties (*14, 15*). Fracture, uniaxial tension, bending, and uniaxial compression tests have been conducted to investigate the overall structural behavior, the modulus of elasticity, and fracture energies of concretes (*16–18*). However, for UHSM, microsteel fibers with high tensile strengths are preferred (*1–5*). Unlike conventional steel fibers, microsteel fibers increase the compressive strength and toughness. However, the optimal amount is usually 2% to 3% as the increase in strength (*19, 20*) levels off at this point, and the workability of the UHSM is negatively affected. In this study, the optimal quantity of steel fibers based on strength and energy absorption capacities of precompressed and heat-cured UHSM specimens is investigated.

Although UHSM can exhibit high target strengths, they have a negative economic and ecological impact (*10*). However, various applications have suggested that the UHSM can be effectively used as a sustainable and economically viable alternative material in steel-concrete composite bridges and conventional prestressed concrete bridge decks (*21–23*). Currently, they are being considered for use in long span resistant panels, shell structures, pavements, prestressed concrete bridge girders, and as an ultra-durable repair material (*24*).

To further investigate the economic viability of UHSM, this research study focuses on developing UHSM from indigenous material rather than prepacked systems to reduce significantly the transportation cost. This study conducted at the Council of Scientific and Industrial Research-Structural Engineering Research Center in Chennai, India, was funded by the government. Because the production of UHSM requires development of appropriate curing regimes, the study focuses on exploring various curing regimes and their potential benefits in increasing the mechanical properties. In addition, the effect of the application of preset pressure was analyzed to determine its impact, if any.

OBJECTIVES

Specific objectives of this study were the following:

1. Determine the individual effects of the addition of microsteel fibers, application of heat treatment, and application of preset pressure on the strength development of UHSM;
2. Determine the mechanical properties of heat-treated UHSM produced from conventionally available materials; and
3. Optimize the amount of microsteel fibers used in production of UHSM, on the basis of the strength development and mechanical properties.

EXPERIMENTAL INVESTIGATION

Materials

The materials used in the production of UHMS include reactive powders, fine aggregate, fibers, water, and high-range water reducers.

Reactive Powders

The reactive powders used in this study include ordinary portland cement (conforming to IS: 12269), silica fume, and quartz powder from a local source. Chemical compositions of the cement and silica fume by percentage by mass are as follows: cement—SiO_2 = 20.49; aluminum oxide (Al_2O_3) = 5.91; iron oxide (Fe_2O_3) = 4.07; CaO = 62.90; magnesium oxide (MgO) = 1.13; sodium oxide (Na_2O) = 0.20; potassium oxide (K_2O) = 0.47; titanium dioxide (TiO_2) = 0.20; manganese oxide (Mn_2O_3) = 0.08; sulfur trioxide (SO_3) = 1.87; silica fume—SiO_2 = 94.73; Na_2O = 0.51. On the basis of BET analysis, the specific surface areas of these powders were found to be 2.3 m^2/kg and 21 m^2/kg, respectively. The quartz powder used in this study contained 99% SiO_2. The particle size distributions of the quartz powder and silica fume are shown in Figure 1*a*. The specific gravities of the cement, silica fume, and quartz used were 3.15, 2.2, and 2.59, respectively.

Fine Aggregate

The fine aggregate used in this study is standard silica sand with a specific gravity of 2.63, meeting the requirements of IS: 650. This sand is available in three grades: 1, 2, and 3. Production of UHSM requires a combination of these grades to meet high the workability, packing density, and super-plasticizer requirements. The sieve analysis of these different sand grades and the well-graded sand combination is shown in Figure 1*b*.

Fibers

High carbon microsteel fibers from Baekerts, London, were used in this study. Their ultimate tensile strengths were 2,000 MPa, and the length and diameter were 6 mm and 0.16 mm, respectively.

Water and High-Range Water Reducers

Potable water was used throughout. Because the w/cm ratio used for the production of UHSM is low, superplasticizers from the polycarboxylate based groups were used in this study.

Mixture Proportions

The four mixture proportions selected for the production of UHSM were based on the lowest w/cm ratio, silica fume–cement ratio, particle size of quartz, packing density of sand (*25*), and fiber content. These four mixtures found in Richard and Cheyrezy and Dugat et al. were subjected to different heat-curing regimes, and the mixture registering the highest compressive strength was selected for the current study (*1–3*). Mixture proportions selected for the UHSM are shown in Table 1. Fiber content was varied in these mixtures from 0% to 3% to obtain strength benefits.

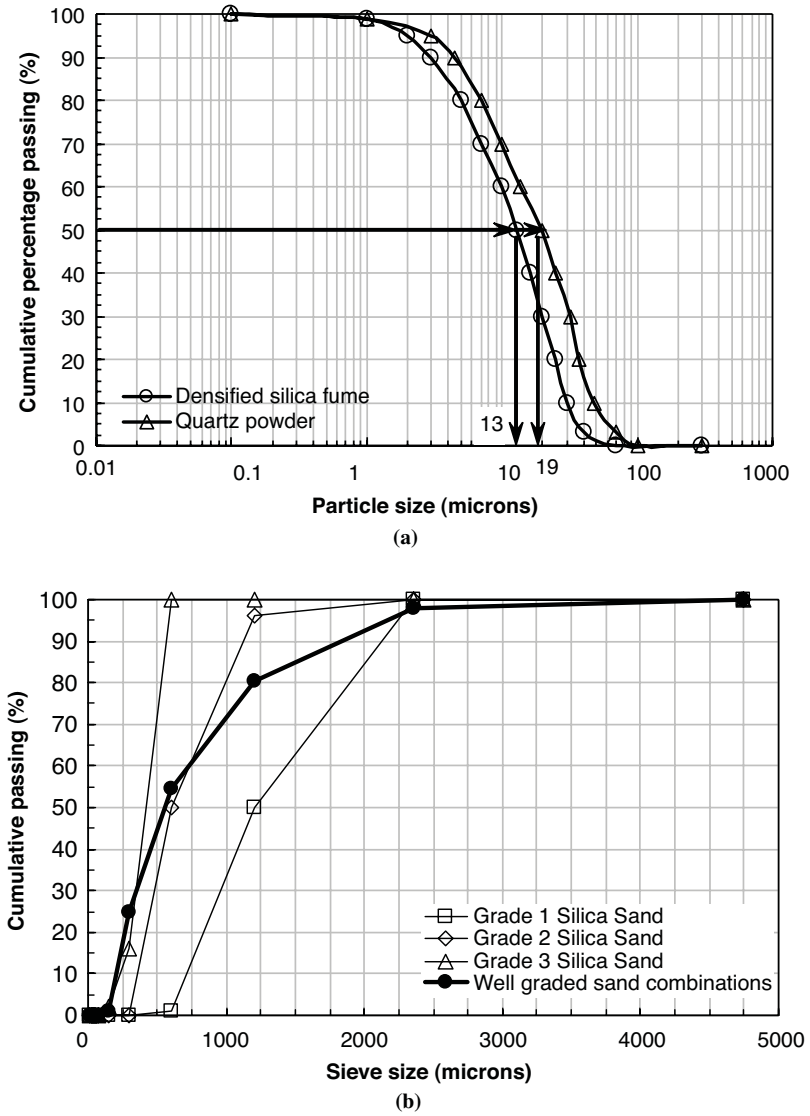


FIGURE 1 Particle size distribution of powders and sand: (*a*) silica fume and quartz powder and (*b*) sieve analysis data of different sand grades and their combination.

TABLE 1 Mixture Proportions of UHSM

		Quantity of Material (per m^3 of mixture)						
Mixture ID	Fiber Volume (%)	Silica Fume (kg)	Cement (kg)	Quartz Powder (kg)	Sand (kg)	Fiber (kg)	Water (kg)	Super Plasticizer (kg)
UHSM-0%	0	202	809	324	890	0	138	30
UHSM-1%	1	200	800	320	880	80	136	30
UHSM-2%	2	198	792	317	871	160	135	30
UHSM-3%	3	196	784	314	862	240	133	30

TABLE 2 Fresh and Physical Properties of Mixtures

Mixture ID	Flow (%)	Theoretical Density (kg/m$^{3)}$	Density (kg/m^3)	Water Absorption (%)	Air Voids (%)	UPV
UHSM-0%	135	2,399	2,297	0.58	4.25	4.79
UHSM-1%	110	2,455	2,385	—	2.85	4.6
UHSM-2%	90	2,511	2,415	0.53	3.82	4.55
UHSM-3%	61	2,564	2,549	—	0.59	—

NOTE: — = not applicable; UPV = ultrasonic pulse velocity.

Mixing Process

Materials were weight batched and dry mixed in a high-speed shear mixer machine for 30 s to achieve initial homogeneity. The superplasticizer was then thoroughly mixed with water before adding it to the dry mixture. Wet mixing was carried out for 5 to 15 min until a homogenous and flowable mixture was obtained. Microfibers were then gradually added to ensure a thorough distribution of the fibers in the wet mixture, with the speed of the mixture machine increasing slowly. The flow table test was used to determine the workability of the resulting UHSM mixtures according to the ASTM C1437 procedure. Then the physical properties of density, water absorption, and air voids were determined after 28 days of curing according to ASTM C642. Ultrasonic pulse velocity measurements were taken according to the ASTM C597 procedure. The fresh and physical properties of the UHSM mixtures are shown in Table 2.

Curing Techniques

The prepared UHSM specimens were allowed to set and harden in standard molds at ambient temperature (25°C) for 24 h before demolding. Then they were immediately subjected to the three curing techniques of normal-water curing (NWC), HWC, and HAC. NWC and HWC were carried out in water baths set at a temperature from 0°C to 150°C, whereas HAC was carried out in an electric oven set at a temperature from 0°C to 300°C.

Experimental Program

Preliminary Investigations with Different Curing Regimes

All the specimens were subjected to Regime 1, Regime 2, Regime 3, and Regime 4 to determine which one resulted in highest compressive strength. Regime 1, which involved only NWC, was used for comparison, whereas Regimes 2 and 3 involved the use of a combination of NWC and HWC for a specified duration. Regime 4 involved a combination of NWC, HWC, and HAC. The precise temperatures over the length of the curing process for the four regimes are shown in the four graphs in Figure 2. Regime 4, which resulted in the highest compressive strength, was used in the rest of the experiments.

Investigation of Rate of Strength Development of UHSM Mixtures With and Without Preset Pressure

For experiments with and without preset pressure, cast UHSM mixtures were poured into a precompression mold to produce cylinder specimens of standard size.

The dimensions and photographs of the precompression mold and the process involved are shown in Figure 3. The precompression mold consists of three parts: top plunger labeled A and B; main body labeled E and C; and base labeled D, G, and H. The function of the base and main body is to hold the mixture, whereas the top plunger transfers the load from the universal testing machine to the mixture. The mold, cylindrical in shape and made of cast iron 25 mm thick, is sufficient to withstand a design vertical load of 60 MPa. The cylindrical mold has high-tension bolt arrangements on the sides, top, and bottom. The diameter of the side bolt is 12 mm, whereas those of the bottom and top are 10 mm. The side bolts are designed to take lateral pressure while the top and bottom bolts are designed to hold the vertical load, which is transferred to the mixtures for a sufficient period of time. The inner dimension of the cylindrical mold is designed to produce specimens of 75 mm in diameter and 300 mm long. These specimens are then cut to standard lengths of 75 mm using a cutting machine. The steps involved in applying preset pressure to the wet UHSM mixture are the following:

- Preparing the wet UHSM mixture having an optimum flow of 25% to 50% and pouring the wet UHSM mixture into the precompression mold;
- Subjecting the mixture to vibration to achieve significant compaction;
- Tightening loosely the high-tension bolts on the top of the precompression mold and placing the precompression mold on the universal testing machine base;
- Applying a preset pressure equal to 45 MPa and tightening the high-tension bolts on the top to hold this preset load for 24 h;
- Loosening the high-tension bolts on the top, bottom, and sides to completely demold the specimen; and
- Cutting the UHSM specimen to desired dimensions.

The cylindrical specimens were then subjected to Regimes 1 and 4 and tested for compressive strength at 3, 7, and 28 days.

Investigation of Mechanical Properties of Heat-Cured UHSM

The wet UHSM mixtures obtained after casting were subjected to Regime 4 without applying preset pressure. All these tests were conducted after the 28-day curing period. The mechanical properties investigated included compressive strength, split tensile strength, flexural strength, and impact strength according to IS: 4031, ASTM D3967, ASTM C348 and ACI 544 procedures, respectively. The size of specimens used were 70-mm cubes, 100- × 200-mm cylinders, 70- × 70- × 350-mm prisms, and 63.5- × 150-mm cylinders for determining the compressive, split tensile, flexural, and impact strengths,

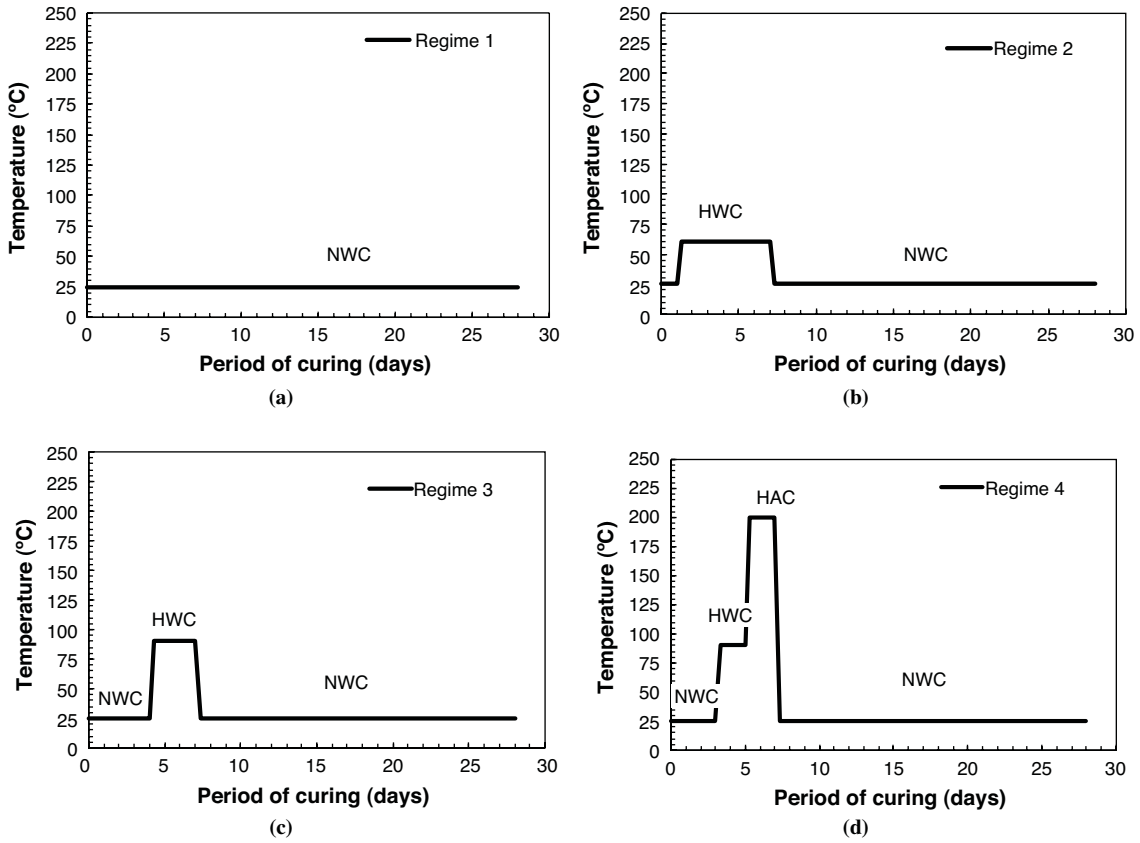


FIGURE 2 Curing regimes adopted: (*a*) 1 day ATC + 27 days NWC at 25°, (*b*) 1 day ATC + 6 days HWC at 60° + 21 days NWC at 25°C, (*c*) 1 day ATC + 3 days NWC + 2 days HWC at 90°C + 22 days NWC at 25°C, and (*d*) 1 day ATC + 2 days NWC at 25°C + 2 days HWC at 90°C + 2 days HAC at 200°C + 21 days NWC at 25°C (ATC = ambient temperature curing).

respectively. In addition to these tests, the energy absorption and toughness characteristics (ASTM C1018) of the UHSM specimens were investigated. The experimental program for investigation of the mechanical properties of heat-cured UHSM is shown in Table 3, and the experimental program for investigation of the effect of preset pressure on the UHSM mixtures is shown in Table 4.

DISCUSSION OF RESULTS

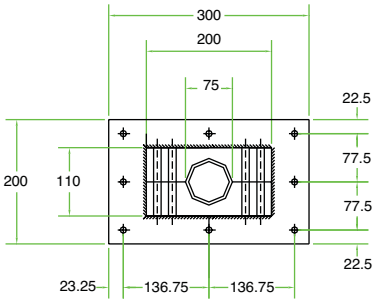
Preliminary Investigation of Effect of Curing Regime

Results from the investigation of the curing regime on the compressive strength of UHSM specimen are shown in Figure 4*a*. As seen in this figure, Regimes 2, 3, and 4 registered higher compressive strengths than Regime 1 (only NWC) by 31%, 5.1%, and 56.4% at 7 days, and 19%, 10.5%, and 37% at 28 days, respectively. This increase in strength may result from the high temperature during the initial curing process that activates cement hydration and pozzolanic reaction. In addition, Regime 2 registered higher strengths than Regime 3 did for two reasons. First, the duration of heat for Regime 2 is longer than for Regime 3, even though the temperature in Regime 3 was higher. Longer durations of heat tend to increase the reactivity of both cement and silica fume, resulting in higher strengths. Second, heat is introduced in Regime 2 specimens 2 days earlier than for Regime 3 specimens. Early introduction of heat tends to activate the cement and pozzolanic reactivity quickly, resulting in higher compressive strengths. The higher compressive strengths obtained in Regime 4 specimens compared with Regimes 2 and 3 may be a result of the high temperature (200°C) used as previous research has shown. Thus, the use of high temperatures activates not only cement and pozzolanic reactivity but also quartz reactivity (*6–10*). Because Regime 4 registered substantially higher compressive strength than the others, this regime was used for all subsequent studies involving heat treatments.

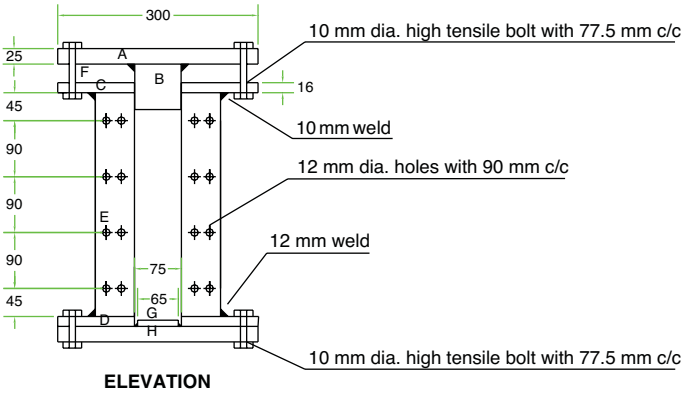
Investigation of Strength Development of UHSM With and Without Preset Pressure

Optimization of Quantity of Microfibers

The rate of strength development of the UHSM specimens both with and without preset pressure and heat treatment is shown in Figure 4*b* through 4*e*. As these parts of the figure show, the compressive strength of UHSM specimens increases with the period of curing until 7 days. For the next 21 days, no further increase is seen in all the mixtures. The compressive strength increases with the increase in fiber addition (from 0% to 3%) for all UHSM mixtures. To understand more fully this effect, the percentage increase in strength was compared with the appropriate control mixture (containing no fibers); these results are shown in Figure 4*f*. As this graph shows, the increase in strength from the 2% and 3% fiber addition in the UHSM and UHSM-P mixtures was ~19% to 22% and ~25% to 28%, respectively.



PLAN



ELEVATION

A - Rectangular plate of L=300 mm; B=200 mm; T=25 mm
B - Circular plate of D=74 mm; T=74 mm
C - Rectangular plate of L=300 mm; B=200 mm; T=16 mm
D - Rectangular plate of L=300 mm; B=200 mm; T=16 mm
E - High tensile bolts, D=12 mm
F - High tensile bolts, D=10 mm
G - Circular plate of D=65 mm; T=10 mm
H - Rectangular plate of L=300 mm; B=200 mm; T=25 mm

(a)

(b)

FIGURE 3 Application of preset pressure on wet UHSM mixtures using a precompression mold: (*a*) dimensions of precompression mold and (*b*) precompression process—(*top*) wet UHSM mixture in precompression mold, (*middle*) application of vertical precompression pressure (45 MPa), and (*bottom*) precompression specimen after demolding (c/c = center to center; L = length; B = width; T = thickness; D = diameter).

TABLE 3 Mechanical Properties of UHSM Determined by Standard Test Procedure

	Mechanical Property					
Mixture ID[a]	Compressive Strength	Split Tensile Strength	Flexural Strength	Impact Strength	Energy Absorption	Toughness
UHSM-HT-0%	X	X	X	X	X	X
UHSM-HT-1%	X	X	X	X	X	X
UHSM-HT-2%	X	X	X	X	X	X
UHSM-HT-3%	X	X	X	—	—	X

NOTE: — = not applicable; HT = heat cured. "X" indicates the mixtures investigated.
[a]Percentage in ID indicates the percentage of fiber in 1 m^3 of the mixture.

TABLE 4 Experimental Program for Precompression Studies of UHSM

Mixture ID[a]	Cured With or Without Heat Treatment	Mixture for Rate of Strength Development
Without Precompression		
UHSM-0%	Without	X
UHSM-2%	Without	X
UHSM-3%	Without	X
UHSM-HT-0%	With	X
UHSM-HT-2%	With	X
UHSM-HT-3%	With	X
With Precompression		
UHSM-P-0%	Without	X
UHSM-P-2%	Without	X
UHSM-P-3%	Without	X
UHSM-P-HT-0%	With	X
UHSM-P-HT-2%	With	X
UHSM-P-HT-3%	With	X

NOTE: P = precompression; P-HT = precompressed and heat cured. X indicates the mixtures investigated.
[a]Percentage in ID indicates the percentage of fiber in 1 m^3 of the mixture.

For the mixtures with heat treatment, UHSM-HT and UHSM-P-HT, the increase in strength with the addition of fibers was higher than without heat treatment. This increase in strength resulting from the 2% and 3% fiber addition was found to be from 40% to 45% and 50% to 52%, respectively. However, because the efficiency of fiber in increasing the compressive strength ceases at approximately 2% to 3% for all the mixtures, 2% fiber content was considered optimum for this study.

Individual Effect of Heat Treatment and Preset Pressure at 2% and 3% Fiber Additions

To understand clearly the individual effects of heat treatment and preset pressure on the rate of strength development of UHSM mixtures, two sets of mixtures were considered, as shown in Figure 5*a* through 5*f*. The first set consists of UHSM-0%, UHSM-2%, UHSM-HT-2%, and UHSM-HT-P-2% mixtures, whereas the second consists of UHSM-0%, UHSM-3%, UHSM-HT-3%, and UHSM-HT-P-3% mixtures. The variable in the first and second mixture is the fiber content (2% for first set and 3% for second set). Similarly, the variable in the second and third mixture is the heat treatment, and in the third and fourth mixture, it is the preset pressure. Figure 5*a* and 5*b* shows the rate of strength development of selected set of UHSM mixtures at 2% and 3% fiber addition, respectively, whereas Figure 5*c* through 5*f* shows the comparison of 7 days and 28 days compressive strengths of these sets of mixtures. As can be seen from Figure 5*a* and 5*b*, the heat-treated mixtures UHSM-HT and UHSM-HT-P exhibit a substantially higher increase in strength than the non-heat-treated mixtures do, especially after 3 days. The higher increase in strength was generally noticed in all the mixtures between the 3-day and 7-day curing period. This period is considered critical in the strength development of UHSM mixtures, in which the immature cementitious matrix having a higher $CaO–SiO_2$ ratio changes to a well-refined and dense cementitious matrix having a lower $CaO–SiO_2$ ratio. For the next 21 days, the increase in compressive strength was minimal for all mixtures. Figure 5*c* and 5*d* shows that the increase in the 7-day strength in the mixtures resulting from the individual effects of fiber addition (2% to 3%), heat treatment, and precompression was 25% to 28%, 75% to 81%, and 8.3% to 9%, respectively. Similarly, Figure 5*e* and 5*f* shows that the increase in the 28-day strength in the mixtures resulting from the individual effects of these three activities was 22% to 25%, 57% to 65%, and 15% to 18%, respectively. The resultant increase in strength from fiber addition may be because of the high ultimate strength of the fibers, whereas the increase in strength as a result of heat treatment may be because of the stiffening of the cementitious paste caused by the pozzolanic reactivity of the silica fume and reactivity of the quartz. The resultant increase in strength from preset pressure may be because of an increase in density and elimination of weaker links in the cement matrix in the fresh state. These results suggest that heat treatment has the largest impact on strength compared with all other studies.

Investigation of Mechanical Properties of UHSM

The compressive, split tensile, and flexural strengths of these UHSM specimens are shown in Figure 6*a*. As shown, the maximum target strengths of 194, 24, and 31 MPa for compression, split tension, and flexure, respectively, were obtained with the UHSM mixtures produced from conventional materials. To better understand the effect of fibers in improving these three strengths, their percentage increase was calculated, as seen in Figure 6*b*. Figure 6*b* also shows that strength increases with an increase in the dosage of microfibers. In addition, a linear trend was seen in the strength versus fiber addition plot. However, for the different strength properties studied, the slopes of the lines were found to be steeper for split tension and flexure than for compression, indicating that fiber addition is more beneficial in improving the tensile strength of UHSM than compressive strength is. The energy absorption characteristics, impact strength, and toughness characteristics of UHSM specimens are shown in Figure 6*c* and 6*d*, whereas the increase in their energy levels is shown in Figure 6*e*. Figure 6*c* shows that energy absorption resulting from compression and impact increases with an increase in fiber content. Similarly, toughness increases with an increase in fiber content from 0% to 2%, as seen in Figure 6*d*. However, at 2% to 3%, toughness tends to level off. Figure 6*e* shows that the increase in fiber content has a less significant impact on energy absorption resulting from compression than from toughness and impact.

CONCLUSIONS

Results from this study suggested the following conclusions:

- The studies involving the different curing regimes indicated that duration and temperature play important roles in increasing the strength of UHSM. Parameters of these regimes could be specified to achieve a desired order of strength.
- Strength development plots of UHSM mixtures showed that
  - The preset and heat-cured UHSM exhibited higher target strengths than did the UHSM in Regime 1.
  - The effect of 45 MPa preset pressure on the compressive strength of UHSM was found to be as high as 15% to 18%. Preset pressure up to 60 MPa has been used in other research to obtain still higher target strengths.
  - The effect of heat treatment on the compressive strength of UHSM was found to be as high as 57% to 75%.

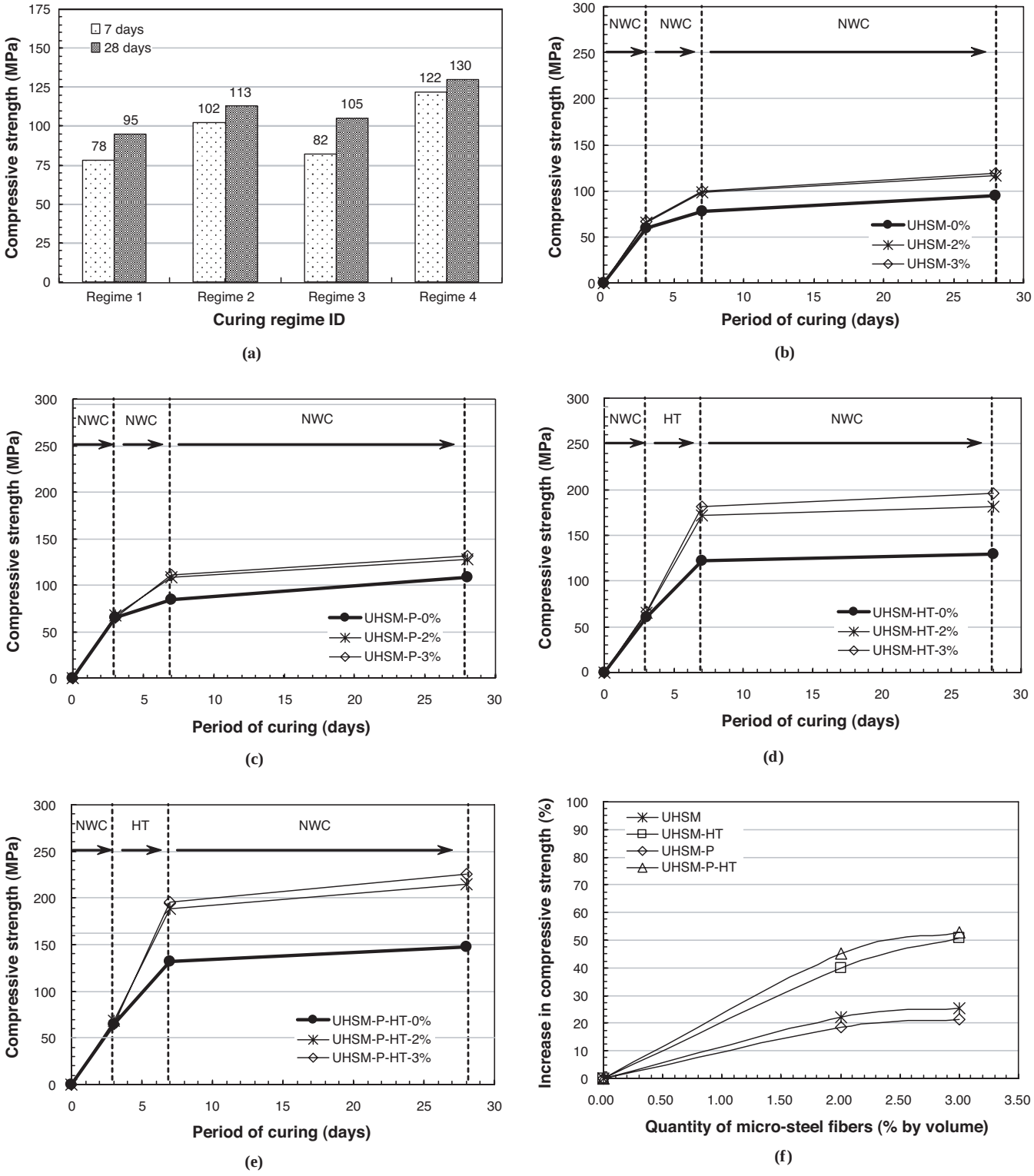


FIGURE 4 Optimization of quantity of microsteel fibers from rate of compressive strength development of UHSM mixtures: (*a*) under different curing regimens, (*b*) without heat treatment and without preset pressure, (*c*) with preset pressure of 45 MPa, (*d*) with standardized heat treatment, (*e*) with preset pressure of 45 MPa and with standardized heat treatment, and (*f*) increase in compressive strength (28 days) with respect to their control mixtures (without fibers).

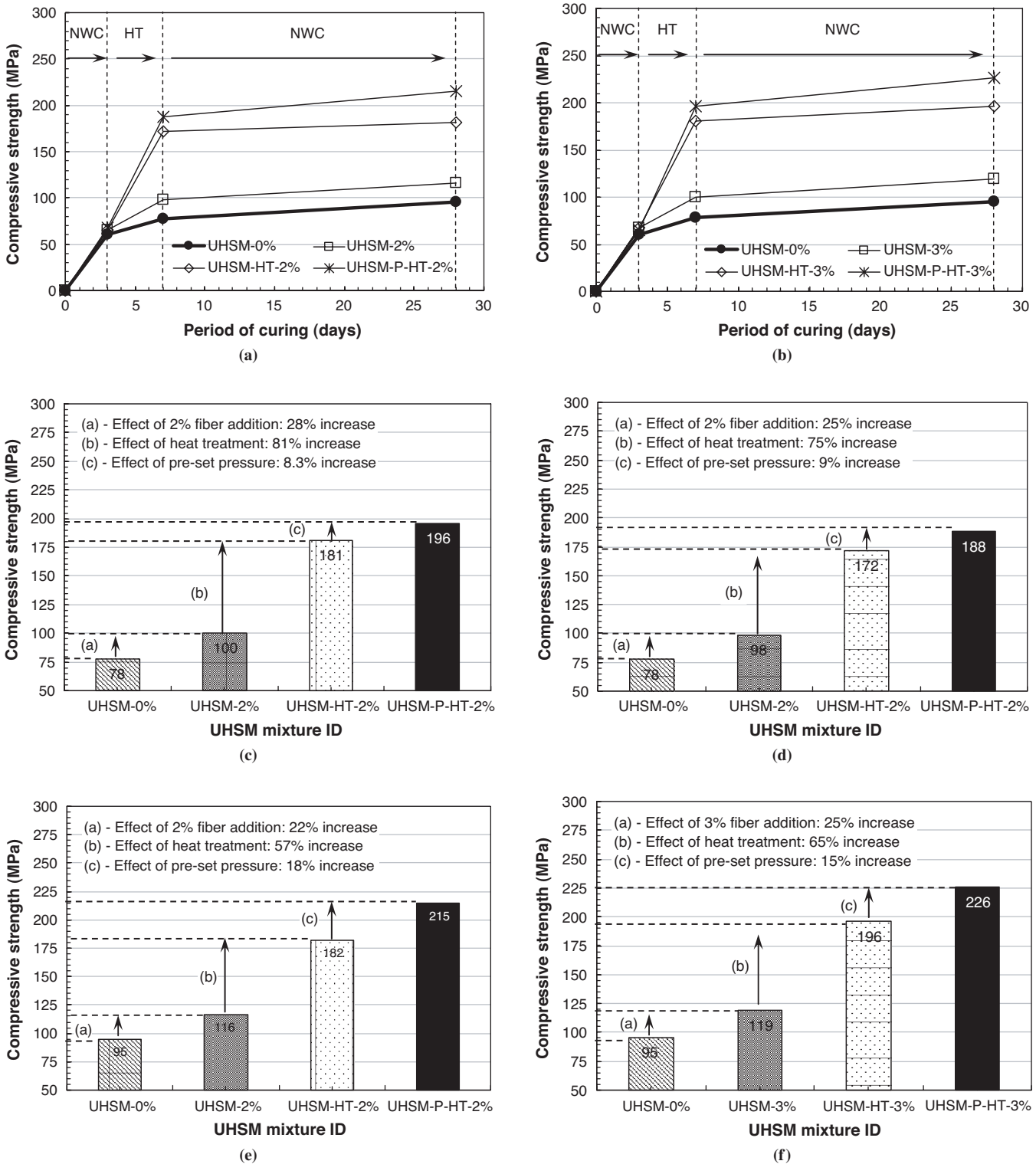


FIGURE 5 Individual effects of fiber addition, heat treatment, and preset pressure on rate of strength development of UHSM mixtures: (*a*) selected mixtures (2% microsteel fibers), (*b*) selected mixtures (3% microsteel fibers), (*c*) mixtures at 7 days (2% microsteel fibers), (*d*) mixtures at 7 days (3% microsteel fibers), (*e*) mixtures at 28 days (2% microsteel fibers), and (*f*) mixtures at 28 days (3% microsteel fibers).

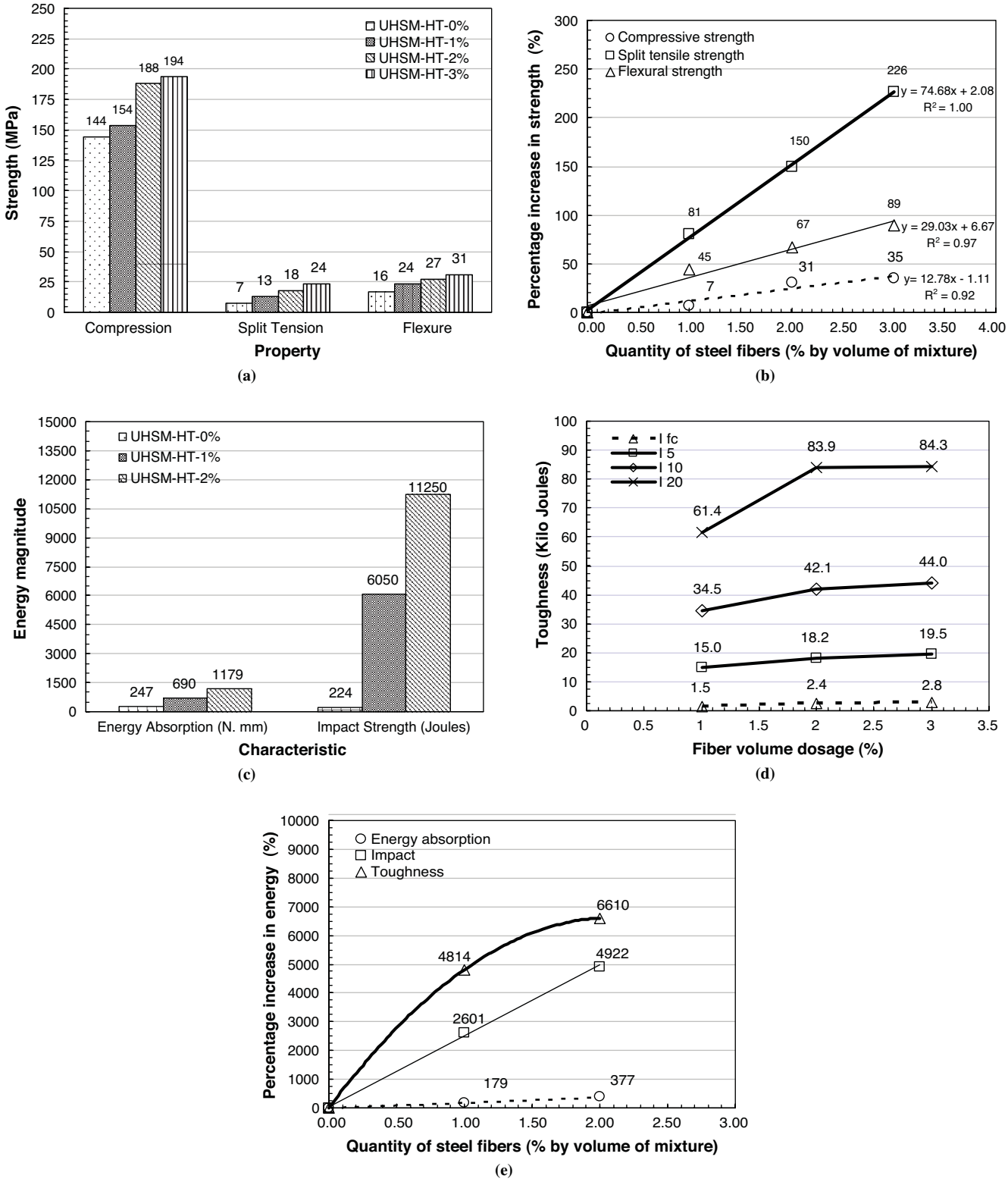


FIGURE 6 Mechanical properties of heat-cured UHSM mixtures at different dosages of fiber: (*a*) strength properties, (*b*) percentage increase in strength with respect to UHSM-HT-0%, (*c*) energy absorption (in compression and impact) characteristics, (*d*) toughness characteristics, and (*e*) percentage increase in energy levels with respect to UHSM-0%.

– The optimum quantity of steel fibers was found to be ~2% to 3%.

– The effectiveness of fibers in increasing the compressive strengths of UHSM was found to be higher for heat-cured specimens than for normal water-cured specimens.

- Results concerning the mechanical properties of UHSM mixtures indicated that

– Higher amounts of microsteel fibers resulted in higher compressive strength, with the optimum quantity being 3% (by volume). However, for workability, the amount was usually limited to 2% (by volume).

– The maximum strengths produced from UHSM mixtures prepared from conventional materials were found to be 194 MPa, 24 MPa, and 31 MPa for compression, split tension, and flexure, respectively.

– The energy absorption characteristics of UHSM resulting from compression and impact were found to increase significantly, up to 2% fiber addition.

ACKNOWLEDGMENT

The authors are grateful to the director of the Structural Engineering Research Center, Chennai, for the full support and encouragement during all phases of the research.

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The Properties of Concrete Committee peer-reviewed this paper.