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EFFECT OF CURING REGIMES ON THE MECHANICAL AND FRESH PROPERTIES OF STEEL FIBER-REINFORCED CONCRETE

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Abstract
Properties of concrete are affected by its fabrication process such as preparation, mixing, placing, finishing and curing. Since curing process is the ultimate stage of the fresh state of concrete before it is put into service, it is of great significance that is needed to be strictly handled. In the present study, steel fiber reinforced concrete was investigated in terms of different curing regimes including precast technology and comparative analysis was performed. To this end, beams and cubes specimens were fabricated and cured under steam process to represent the applications of precast concrete industry. Findings were compared with the other types of curing regimes. Mechanical behaviors of specimens were evaluated along with their strength development and workability in the presence of steel fiber. Results indicated that adequate workability and mechanical properties were obtained for steam-cured specimens compared to other specimens produced with different curing regimes. However, production parameters such as mixture proportion and fiber dosage were more pronounced for low-strength concrete specimens compared to high strength steam cured concrete specimens.

Keywords: **Mechanical properties; Precast concrete; Steam curing; Steel fiber.**

1. INTRODUCTION

Mechanical and durability performance of concrete depends on its production processes such as production, mixing, pouring and curing. Before concrete is brought into service, final process is the curing of concrete which is susceptible to different environmental conditions. For instance, atmospheric steam curing is essential to accelerate the strength development of concrete in precast concrete industry. Since hydration capability increases with the increment of temperature, steam generation in atmospheric pressure can provide high early-age strength for concrete practices [1]. Steam curing temperature generally adopts curing temperature between 50-100°C although most of steam curing process varies between 65-85°C in precast concrete plants [2]. Duration of steam curing and temperature is evaluated by taking into account 1-day strength value of fabricated concrete together with economic and energy-saving considerations. Thanks to proper utilization of steam curing, concrete can reach more than 60% of the 28-day old concrete strength level within 24 hours. Appropriate curing cycles are generally selected as a compromise between early and ultimate strength values. However, the application of steam curing still includes concerns such as the probability of increased moisture loss during curing process and potential loss of long-term engineering properties [3]. These concerns can be highly pronounced in low/moderate strength concrete especially designed at 20/25 MPa. As concrete designed with 25 MPa-compressive strength dominates 846-megajoule energy requirement for the annual world concrete production [4], more investigation needs to be carried out for the low/moderate concrete classes to sustain safe applications in precast industry.

Mixture composition has also critical influences on the mechanical properties of steam-cured concrete. Cement type, aggregate amount and water/binder ratio have an impact on the quality and assurance of different concrete classes produced with steam curing [5–8]. In the mixture design, fibers can be also randomly used to tailor mechanical properties in tension zone. To strengthen tension zone [9] and prevent further deterioration of concrete [10], different types of fiber-reinforced concrete draw attention and comprises randomly dispersed fibers [11]. The use of different types of fibers such as steel, glass, and synthetic fibers have provided delaying of additional crack development in concrete through bridging micro-cracks [12]. Furthermore, fibers serve the formation of more distributed and multiple cracks thus significantly reduce the permeability of concrete [13] and increase energy-absorbing capability [14–15]. Besides hardened properties, different fiber types also affect the workability properties of the mixtures based on their individual shape, length, volume and aspect ratio. Therefore, workability properties should be also addressed by preventing bundled fibers in the concrete mixtures. Accordingly, uniform distributed fibers can assure targeted fresh and mechanical properties. One of the common fibers used in fiber reinforced concrete is the steel fiber [16] which has different individual properties. Generally, fresh properties of steel fiber reinforced concrete are controlled by the ratio of length to diameter (aspect ratio) of fibers and volume fraction in the mixture design. The ratio of steel fiber dosage ranges from 0.5% to 1.5% by weight of total mixture and ratio of length to diameter is mostly used between 50 and 100. The higher aspect ratio of the fibers can provide preferable pull-out resistance especially under flexural loadings since the interfacial surface area increases with the concrete. On the other hand, a higher aspect ratio of fibers can exhibit lower workability properties and appropriate mixing may not be achieved. This would be once more critical for the low/moderate concrete class which are designed according to boundary conditions given in relevant standards. Although numerous studies have investigated different properties of steam cured concrete [17–23], a limited effort is available in the literature for the low/moderate strength class of steel fiber reinforced concrete in terms of

Figure 1.
Aggregates for each size; a) 0–4 mm b) 4–12 mm c) 12–22 mm

Table 1.
Physical properties of aggregates

	0–4 mm	4–12 mm	4–12 mm
	(0-0.16 inches)	(0.16-0.47 inches)	(0.47-0.86 inches)
Specific gravity	2.66	2.67	2.68
Water absorption rate (%)	2.50	0.50	0.50
Dry weight	487	903	547
Saturated surface dry weight	500	907	549

Table 2.
Physical and mechanical properties of steel fibers

Fiber type	Length (mm)	Diameter (mm)	Aspect ratio	Density	Tensile strength (MPa)
Steel fibers	60 (2.36 inches)	0.75 (0.03 inches)	80	7.48	1050 (min.)

Table 3.
Material amounts of mixtures and acronyms of specimens

Materials	**Kg in 1 m^3**	**Lb in 1 ft^3**
Cement	295	18.41
Water	174.3	10.88
Chemical additive	2.655	0.166
0-4 mm aggregate	321	20.04
4-12 mm aggregate	1153	71.98
12-22 mm aggregate	423	26.40
Steel fiber	25	1.56
WP-3, WP-7, WP-28	**W**ater-cured **P**lain specimens at **3, 7** and **28** days, respectively	
WS-3, WS-7, WS-28	**W**ater-cured **S**teel fiber reinforced specimens at **3, 7** and **28** days, respectively	
AP-3, AP-7, AP-28	**A**ir-cured **P**lain specimens at **3, 7** and **28** days, respectively	
AS-3, AS-7, AS-28	**A**ir-cured **S**teel fiber reinforced specimens at **3, 7** and **28** days, respectively	
SP-1, SP-7, SP-28	**S**team-cured **P**lain specimens at **1, 7** and **28** days, respectively	
SS-1, SS-7, SS-28	**S**team-cured **S**teel fiber reinforced specimens at **1, 7** and **28** days, respectively	

strength development and workability properties. Therefore, this paper deals with the effect of steam curing on the mechanical and workability properties of steel fiber incorporated concrete mixtures. Mixture design was made based on the targeted 25 MPa compressive strength and steam curing was applied to specimens to evaluate engineering properties at different ages. Workable mixtures were also provided in the use of steel fibers. For comparison, water and ambient curing regimes were also applied for steel fiber reinforced concrete mixtures and control mixtures at each predetermined curing age.

2. EXPERIMENTAL PROGRAM

2.1. Materials

The cement used was a commercially present Portland Cement (CEMII/A-M (P, L) 42,5R) similar to ASTM Type IL cement which includes limestone as an ingredient between 5–15% [24]. Preferred cement is in conformity with TS-EN 197-1 [25]. A–M abbreviations mean 6–20% mineral additives in blended cement while P refers to pozzolan and L refers to limestone. The water used in the study was drinkable water at pH 6.58. In all mixtures, high range water reducer (HRWR) was used to provide homogenous mixtures in conformity with the TS EN 934-2 [26]. Crushed stone aggregates were used in the preparation of mixing. Physical properties of aggregates were given in Table 1 and images of aggregates for each size were presented in Figure 1.

Hooked-end steel fibers having an aspect ratio (length/diameter) of 80 were used in the experiments in accordance with the TS EN 10513 [27]. The aspect ratio of hooked-end fibers was selected according to mixtures to provide resistance to pull out and enhance ductility in the specimens. Since length of steel fibers is longer than 40 mm (1.57 inches), dimensions of beam specimen were selected as 150×150×750 mm (width×height×length [5.90-5.90-29.52 inches]) in conformity with TS EN 10515 [28]. Mechanical and physical properties of steel fibers were given in Table 2.

2.2. Preparation of specimens

Mixtures were produced with a 0.6 water/cement ratio. Steel fiber dosage (1% by weight of total mixture) was kept constant for each curing regime. Mixture proportioning and acronyms of the mixtures were presented in Table 3.

Mixtures were produced in the concrete batch mixer with a capacity of 50 liters in the laboratory. Three specimens from each group were fabricated as follows; i) Dry mix of differently sized aggregates for two minutes ii) addition of half of the water and half of the superplasticizer during dry mix iii) addition of cement with other half of the water and half of the superplasticizer and mixing for four minutes iv) gradual addition of steel fibers over three minutes period to prevent fiber flocculation v) continue of mixing for additional five minutes until a homogeneous mixture was achieved. Visual observations were made to assure the uniformly dispersed steel fibers in concrete mixtures. Mixtures were poured into the molds at two stages and external compaction was provided by utilizing concrete vibrator. Mixtures were vibrated for 5–10 seconds.

Figure 2.
a) water, b) air and c) steam curing

2.3. Curing

Mixtures were prepared in accordance with TS EN 206 Standard [29]. Three types of curing regimes such as water curing, air curing, and steam curing were applied. The air-cured specimens were kept at an ambient temperature of laboratory environment (23±2°C) while water-cured specimens were kept in a water tank in conformity with TS EN 12390-1 [30]. In steam curing, a sensitive thermometer probe was inserted under the steam covers to control the temperature of steam, as stated in regulations [31]. Covers were placed over the specimens immediately after the delay period. Free circulation of steam around the test specimens was provided under the covers. Different curing regimes used in the study were given in Figure 2.

Since the duration of steam curing and the maximum temperature have a significant effect on the development of hydration, steam curing application was taken into account sensitively for the low-strength

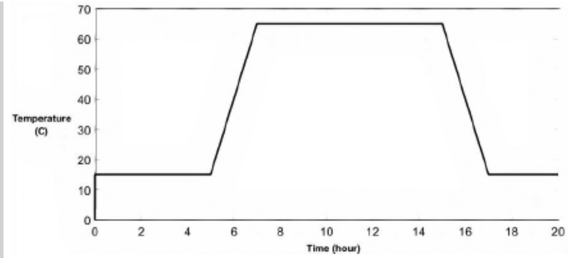

Figure 3.
Applied steam curing duration and temperature

Figure 4.
Mechanical testing of specimens a) Schematic demonstration of flexural tests; 375 mm (14.76 inches), 600 mm (23.62 inches) 750 mm (29.52 inches) b) Flexural tests c) Compression tests

Table 4.
Application process of steam curing

Max. temperature (°C)	Initial temperature (°C)	Delay period (hour)	Increment/decrement of temperature (°C /hour)	Duration of max. temperature	Total duration steam curing (hour)
65	15	5	25	8	17

concrete mixtures. Taking into account the debate over the delay period of steam curing application [32, 33], delay period exceeded the final setting time of cement used in this study as it is tested in preliminary experiments. The final settting time for the cement was 202 min equivalent to 3.36 hours. Therefore, steam curing cycle comprised a delay period of 5 hours. Although selection of delay period is more pronounced in applications where the maximum temperature is high (more than 80°C), a 5-hour delay was applied in the study to offset any probable defects during incomplete cement hydration under steam curing. The cycle comprised a total of 17 hours steam curing under canvas steam chamber. Maximum heat temperature was 65 +-5°C and other details were given in Table 4 and Figure 3.

2.4. Testing

A total of 150-mm 54 cubic specimens and 9 beam specimens (150×150×750 mm) corresponding to more than 340-liter of concrete was produced. For water and air cured concrete mixtures, 150 mm (5.90 inches) cubic specimens were tested at the age of 3, 7 and 28 days to evaluate the compressive strength. Steam cured specimens were tested in the same order. However, steam cured specimens were tested under compressive loading at first day after production since it was not possible to compare 1-day old air and water cured specimens with 1-day old steam cured specimens in terms of early age development. A testing machine with 3000 kN capacity was used during the experiments and loading rate was 0.9 kN/sec for compressive loadings while 0.1 kN/sec was applied for flexural loadings. Three specimens (150×150×750 mm) produced from each mixture were used for flexural tests at 28 days by loading at 1/3 points on a span of 600 mm (23.62 inches). Testing procedure of the study has been given in Figure 4.

In the study, workability properties of mixtures were evaluated by conducting slump tests for both plain and fiber reinforced mixtures. Each fresh mixtures were poured into a cone-shaped mold and slump values (Figure 5a-c) were recorded by turning upside down the cone-shaped mold in accordance with TS EN-12350-2 [34] and then poured into molds (Figure 5d). In addition to slump tests, each specimen was weighed before tests and average values were recorded for each mixture (Figure 5e).

3. RESULTS AND DISCUSSIONS

3.1. Workability properties

Fresh properties of each mixture were evaluated according to TS EN 12350-2 [34] short after cement-to-water contact. Generally, fresh mixtures have demonstrated that reinforcement of steel fiber has led to decrease in workability properties in contrast to plain mixtures. Fresh plain mixtures had 13 cm (5.19 inches) average slump values whereas fresh steel fiber reinforced mixtures had 11.5 cm (4.52 inches). In the presence of steel fibers, the behavior of fresh mixtures has resulted in lower flowability. As it is known, estimation of workability for mortars and concrete mixtures is considered by taking into account viscosity parameter [35]. Although viscosity criteria are more appropriate for Newtonian liquids [36], current applications such as T50, J-ring, V Funnel and slump flow tests are utilized with the aim of prediction for the workability of concrete mixtures. However, only self-compacting concrete can be regarded as Newtonian liquids and viscosity parameter is heavily influential on workability properties [36]. Utilization of slump flow test in this study is one of the experiments preferred in the literature that considers viscosity parameter [37, 38, 39]. Despite the fact that steel fiber reinforced fresh mixtures cannot be regarded as a fully Newtonian liquid, viscosity parameters indicated in the slump tests were considered as consistency values for both mixtures (i.e plain and steel fiber reinforced mixtures) in this study. Selection of slump tests was preferred intentionally since a number of studies have reported that other current applications such as Vfunnel test are inadequate to determine workability [40] due to clogging of fibers in apparatus. Experiments in slump flow tests have exhibited that steel fiber reinforcement has caused decrement at the rate of 11.5%.

It is known that poor fiber dispersion reduces the workability and stability of matrix. Although well-dis-

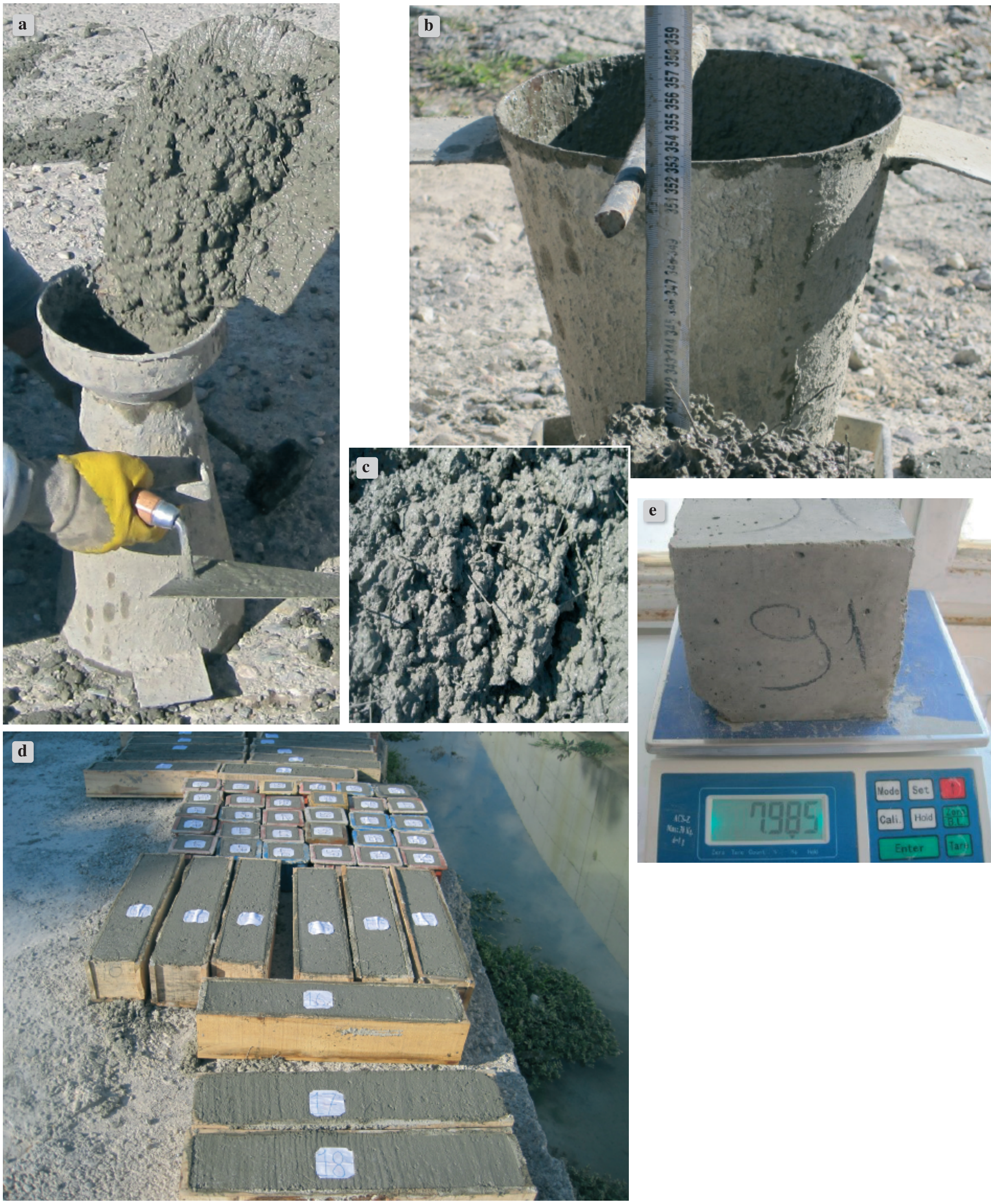

Figure 5.
Workability tests (a-c); mixtures in molds (d); weights of specimens (e)

tributed steel fibers were achieved in all fresh mixtures, the reason of decrease in the slump values of fresh steel fiber reinforced mixtures is most probable due to increased surface area of the overall matrix. Addition of fibers could have caused more surface area for matrix and this have led to decrease in workability. The lowest and highest slump values of mixtures were 11.3 and 13.2, respectively. These results

Table 5.
Measured unit weight and slump values of the mixtures

Mix ID	Average Unit weight (gr/cm^3)	Average Unit weight (lb/gal)	COV* in unit weight (%)	Average Slump value (cm)	Average Slump value (inches)	COV* in slump value (%)
WP-3	2.34	19.44	0.98	12.90	5.08	1.25
WP-7	2.34	19.49	0.24	12.93	5.09	0.34
WP-28	2.34	19.50	0.65	13.03	5.13	1.60
WS-3	2.34	19.50	0.65	11.53	4.54	1.33
WS-7	2.35	19.60	1.47	11.80	4.64	0.86
WS-28	2.32	19.38	0.49	11.63	4.57	1.82
AP-3	2.33	19.47	0.24	12.87	5.09	1.87
AP-7	2.34	19.49	1.50	12.83	5.05	0.46
AP-28	2.34	19.49	0.24	12.93	5.09	1.20
AS-3	2.35	19.63	0.64	11.27	4.43	1.28
AS-7	2.31	19.24	1.09	11.33	4.46	1.37
AS-28	2.33	19.47	0.89	11.30	4.45	0.79
SP-1	2.33	19.44	1.13	13.03	5.13	1.60
SP-7	2.33	19.47	1.23	13.07	5.14	1.87
SP-28	2.30	19.19	1.99	13.20	5.20	0.68
SS-1	2.31	19.25	0.50	11.50	4.52	0.89
SS-7	2.32	19.36	0.43	11.27	4.44	0.52
SS-28	2.28	19.02	1.31	11.77	4.63	2.06

are both within the limit values of S3 category which indicates that utilization of both mixtures are appropriate for professional construction sites where concrete vibrator is used according to TS-EN 206 [29]. It is worth noting that a higher w/c ratio of mixtures could not have provided highly workable mixtures in the category of S3 (TS-EN 206) [29] without adding chemical admixture. It should also be noted that higher slump values do not directly mean higher workability properties. However, there is a high correlation between slump values and workability properties in the applications. Rheological properties of each material and total mixture should be investigated for precise workability characteristics in the further studies. During preliminary experiments, it was also inferred that aspect ratio and volume fraction of fibers had impact on slump values. Higher fiber volume fraction and aspect ratio triggered poor workability so that fiber clumping was obtained in the mixtures. Therefore, preliminary studies have been guideway for actual experiments for the purpose of adequate workability. These results were consistent with the results existing in the literature [41–45]. Accordingly, selected fractions and aspect ratio of steel fibers exhibited advisable performance in terms of fresh properties. Besides homogeneous mixture which is essential for the hardened performance of specimens, practical casting of the mixtures with obtained workability properties is appropriate for both cast-in-place and precast concrete. All slump results and assessed unit weight of each mixture have been given in Table 5.

3.2. Mechanical Properties

3.2.1. Compressive Strength

Table 6 and Figure 6 demonstrate the results of compressive strength test at 1, 7 and 28 days for steam cured concrete specimens and at 3, 7 and 28 days for air and water cured specimens. The results indicate that compressive strength of specimens increased with progress in age regardless of curing type and fiber introduction. It is clear that the increase of compressive strength is due to ongoing hydration process within the maturation of mixtures. As it can be inferred from the Table 6 and Figure 6, average compressive strength of 1- and 7 day-old steam cured plain specimens (13.64 and 23.20 MPa, respectively) surpassed the 3- and 7-day-old air and water cured plain specimens (11.87–19.96 MPa for air cured plain specimens and 11.90–22.66 MPa for water cured plain specimens, respectively). The compressive strength of 1-day old steam cured plain specimens was approximately 15% higher than the 3 days old air and water cured specimens. On the other hand, 7 days old steam cured plain specimens had 16% higher compressive strength value than 7 days old air cured plain specimens while it was only 2% increase

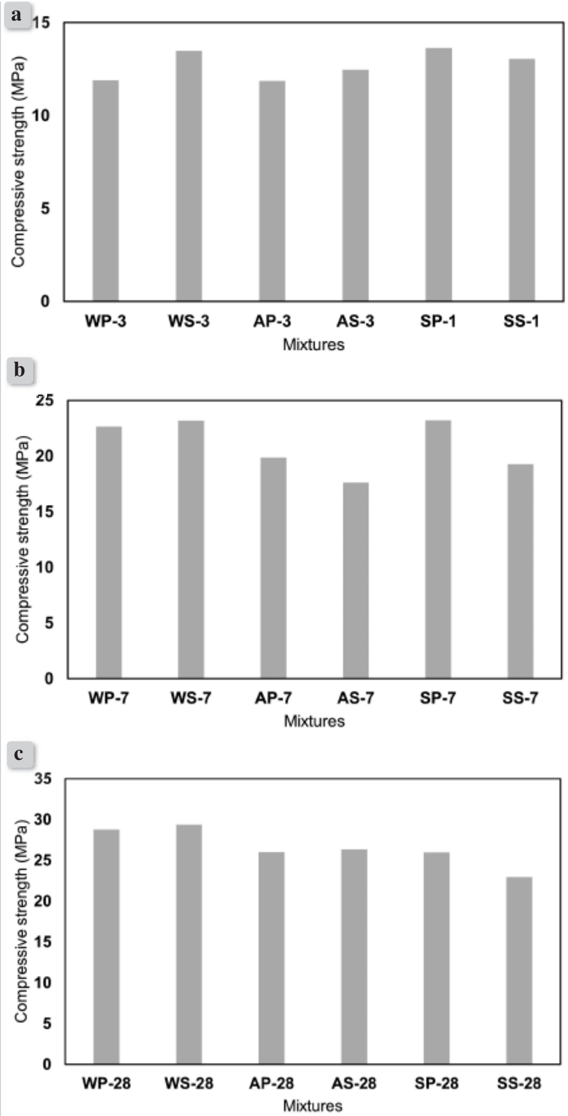

Figure 6.
Average compressive strength of mixtures at different ages (a-c)

compared to 7 days old water cured plain specimens. The early age strength gain by the utilization of steam curing is due to high temperature that accelerated the cement hydration of mixtures. The abovementioned results were satisfying for the strength gain rate at early ages taking into account the TS EN 3648 Steam Curing of Precast Concrete Products under Atmospheric Pressure-Turkish Standard [46]. In conformity with related Turkish Standard, all 1-day old steam cured specimens were above the 60% of the 28 days old compressive strength. Although higher early-age strength development is clear for the 1- and 7- day-old steam cured plain specimens, reduction of compressive strength values can be seen at 28 days.

Table 6.
Compressive strength of mixtures

Mix ID	Average compressive strength (MPa)	COV in compressive strength (%)
WP-3	11.90	5.21
WP-7	22.66	11.09
WP-28	28.76	11.37
WS-3	13.49	8.44
WS-7	23.18	4.87
WS-28	29.38	3.37
AP-3	11.87	10.48
AP-7	19.86	15.78
AP-28	26.04	12.76
AS-3	12.48	8.10
AS-7	17.62	13.63
AS-28	26.35	15.19
SP-1	13.64	10.16
SP-7	23.20	0.54
SP-28	26.00	1.84
SS-1	13.06	7.06
SS-7	19.27	2.07
SS-28	22.96	3.66

This behavior is consistent with studies present in the literature [47–49], however, reduction is more pronounced in steam cured plain specimens compared to water cured plain specimens in this study since the detrimental effect of steam curing at later ages is more influential on low strength class concrete. The average compressive strength of water cured plain specimens was 9.6% higher than the steam-cured plain specimens at 28 days. On contrary to the performance of steam-cured high strength concrete, this reduction can be considered more critical although maximum temperature (65°C) used in the study was not so detrimental in other studies [5, 50]. The reason for approximately 9.6% reduction in compressive strength can be attributed to a rate of hydration products at early ages that inhibit further hydration development. Generation of larger hydration products may have led to hindering of potential hydration products at later ages by preventing water to contact with dry cement particles. For this reason, steam cured plain specimens exhibited lower compressive strength at 28 days compared to other specimens. In addition to that, during the steam curing, the different thermal expansion coefficient of cement, water and aggregates could have played a role in the reduction of compressive strength since low strength concrete mixtures are more prone to additional microcracking development and increased porosity.

The compressive strength of steel fiber incorporating specimens can be also seen in Table 6. Considering the values of Table 6, WS-3, AS-3, and SS-1 specimens exhibited similar compressive strength behavior. However, steam cured steel fiber reinforced specimens had lower compressive strength with respect to air and water cured steel fiber reinforced specimens in further ages. This result is clearer for the 28 day-old specimens. SS-28 specimens had 21.8% and 14.2% lower compressive strength compared to WS-28 and AS-28 specimens, respectively. The reasons for decreased compressive strength at 28 days are not different than the reasons stated for plain specimens. Increased hydration rate and larger hydration products in the consequence of higher temperature block the unhydrated cement particles to react with water so that lower compressive strength is obtained in steam cured steel fiber reinforced specimens at later ages. However, it seems that reduction is more notable in steam cured steel fiber reinforced specimens than the reduction in steam cured plain specimens. This result can be due to the different thermal expansion coefficients of steel fibers along with other concrete ingredients. Although reinforcement steel and conventional concrete have similar thermal expansion coefficient (1-1.2 x 10^{-5}C), the slight difference could have led to more reduction in compressive strength due to weakened interfacial transition zone (ITZ). However, further studies should also be performed with microanalysis to ensure the reason of reduction. Considering the water and air cured specimens, hydration development is thought to be more stable and uniform generation of hydration products provide higher mechanical performance than those of steam-cured steel-reinforced specimens. Irrespective of curing type, steel fiber reinforced specimens had a slight improvement in average compressive strength for WS-3, WS-7, WS-28, AS-3 and AS-28 specimens in comparison with the WP-3, WP-7, WP-28, AP-3 and AP-28 specimens. This improvement can be related to uniform dispersion of steel fibers into the matrix so that fibers could have gained the increased capability of delaying micro-crack and blocking crack propagation up to certain level under compressive loadings.

It should also be noted that air cured specimens, regardless of fiber reinforcement, resulted in lower compression strength in comparison with the specimens cured in air at 7 and 28 days. This is because hydration products did not continue precisely in air curing whereas water saturated specimens were favorable for ongoing hydration process.

As can be seen in the results, three curing regimes resulted in different influences on the compressive strength of same mixtures. These results can be associated with the fact that existence of the fibers may not have contributed to the improvement of load-bearing capacity under compression loadings due to shear modulus of fibers that may be similar to concrete. Results also indicate that ineffectiveness of steel fibers was more pronounced for the steam cured specimens under compression tests. The heat curing may have presented a slight drawback for compressive strength of the steel fiber reinforced specimens. For example, Cecini et al. (2018) states that elevated temperature compared to other curing regimes triggers a more porous microstructure at fiber-matrix interface leading to slight reduction in compressive strength of concrete [22]. In addition, Zheng et al. (2018) supports that steel fibers were more efficient in the presence of high-strength concrete. As this study aims to investigate these effects in the low/moderate strength concrete (25 MPa), steam curing may have worsened the favorable steel-fiber effect for compressive strength due to probable higher porous microstructure [51]. Results were also in line with the recent study of the Thorstensen, (2020) where they found out that influcence of steel fibers on the compressive stregnth of the concrete is still debatable [52].

3.2.2. Flexural Strength

Table 7 demonstrates flexural strength (modulus of rupture) values of the specimens. Experimental mean values were computed from the average of three-beam specimens by using the equations of 3-point bending. Parameters were σ, M, W, P, L, b, and h which refers to ultimate flexural strength, moment of inertia, maximum load, the length between supports, width and height of the specimen, respectively.

As seen in Table 7, irrespective of curing type, steel fibers provided an improvement on flexural strength of the test specimens. Taking into consideration of

Table 7.
Flexural strength of mixtures

Mix ID	Average max. flexural load (kN)	Average flexural strength (MPa)	COV in flexural strength (%)
WP-28	15.22	4.06	16.28
WS-28	18.61	4.97	15.19
AP-28	14.80	3.95	13.37
AS-28	17.07	4.55	2.01
SP-28	15.30	4.09	16.43
SS-28	16.86	4.50	10.98

Figure 7.
Improved crack growth resistance on beams specimens

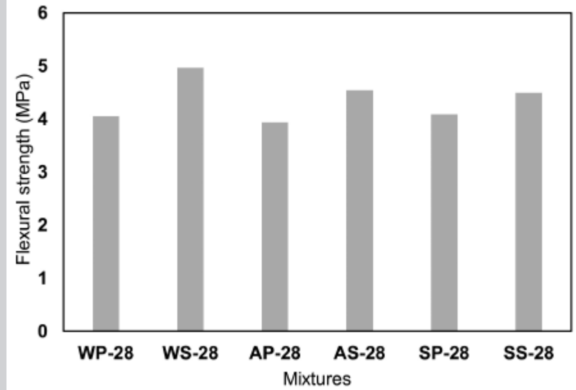

Figure 8.
Average flexural strength of mixtures at 28 days

WP-28 beam specimens, the obtained improvement was 22% compared to steam cured plain specimens. Although such increase was not observed in other beam specimens, AS-28 and SS-28 exceeded values of AP-28 and SP-28 at a rate of 13% and 9.1%, respectively. However, 22% increase of flexural strength of WP-28 mixture compared to plain counterparts was an inadequate flexural enhancement in contrast to studies related to high strengh concrete class (40 MPa) produced with the same steel fiber ratio and specimen size [53]. This result is consistent with the studies in the literature where mechanical improvement in high strength concrete is more explicit than low strength concrete [55]. The reason for such behavior can be attributable to advanced bond characteristics of the steel fibers and the matrix in high strength concrete mixtures. Despite the fact that high strength steel fiber reinforced concrete provides higher flexural strength [55], as it can be seen in Figure 7, WS-28, AS-28, and SS-28 specimens improved the post-cracking flexural behavior. In all specimens, steel fiber reinforcement had played a great role on crack growth resistance.

Water cured steel fiber reinforced specimens resulted in higher flexural strengths in comparison with steam and air cured steel fiber reinforced specimens, as expected. On the other hand, plain concrete specimens had similar flexural behavior regardless of curing type as seen in Table 7. However, in the presence of steel fiber, the flexural strength of beam specimens was found to be more susceptible to curing regime. For example, the average flexural strength of WS-28 specimens was 8.45% and 10.44% higher than the AS-28 and SS-28 specimens, respectively. Although AS-28 and SS-28 resulted in similar flexural strength values, water curing was clearly more effective than other curing types in the improvement of flexural strength. The behavior of water cured steel fiber reinforced concrete specimens was also similar in other study in the literature [56].

Compared to water and air cured steel fiber reinforced test specimens, SS-28 specimens resulted in lower flexural strength (Figure 7). The reason of reduction in the flexural strength of SS-28 can be due to an increased proportion of large pores in cement paste resulting from steam curing. Steam curing regimes can lead to detrimental alteration in porosity and pore size distribution that can significantly reduce mechanical properties. Both the steam curing and its duration have a significant influence on hydration process and results show similar findings in the literature [57]. Another finding recorded in the study was the higher variability of flexural strength values of SS-28 and SP-28 compared to air and water cured specimens. Concrete comprises cement paste, aggregate and interfacial transition zones (ITZ) [58] and ITZ is known as the weakest phase of the concrete and the microcracks in ITZ lead to a change of cement based composites from linear behavior to the non-linear behavior under loading [59–60].

Accordingly, high temperature may have led to the formation of defects in the concrete in steam curing and randomly increased defects in ITZ could have been the reason for such variability. Similar results were also reported from the study dealing with steam cured concrete properties [61]. Also, the effect of thermal expansion of steel fibers and concrete could be more explicit in the case of steam curing. This formation can be responsible for the worsened bond characteristic between matrix and steel fibers. For example, steel fibers undergo different strains in terms of thermal expansion in concrete environment between different elevated temperatures [62]. Although this was not adequate to lead higher reduction in mechanical strength, one reason can be associated with the thermal expansion of mixture ingredients in different curing regimes for the obtained slight fluctuations in the results. Another explanation can be made based on study of Lau and Anson [63] where they support that elevated temperatures during curing process have led to higher reduction in steel fiber reinforced concrete in comparison with their plain counterparts. In addition, faster dehydration of the concrete during steam-curing could be another reason for flexural strength reduction.

4. CONCLUSIONS

This paper investigated the steam-cured low/moderate strength concrete mixtures with an emphasis on its effects in mechanical and workability properties. Results clearly indicate concrete mixtures having that low/moderate compressive strength class (25 MPa) are highly affected by curing parameters. This was even more pronounced in the case of steel fiber reinforcing in comparison with ambient and water curing. Following conclusions can be drawn from the findings of this study;

- Incorporation of steel fibers reduced the workability properties of mixtures although they were distributed homogeneously as interpreted from mechanical properties. However, selection of w/c ratio, use of superplasticizer and aspect ratio of steel fibers were appropriate to sustain plastic fresh concrete mixtures within standards.
- Early-age compressive strength development in low/moderate concrete was more responsive to curing parameters. However, all compressive strength values of 1-day old steam cured specimens were at least more than half of the 28-day target strength level (25 MPa). Although results were promising for conventional precast requirements, some results were questionable in terms of higher coefficient of variations. This implies that attention should be paid to mixture designs and curing conditions even if lower maximum temperature (65°C) is applied in steam curing applications. Although 65°C steam curing is considered as unharmful maximum temperature in most cases, curing parameters should be additonally controlled for the steel-reinforced low/medium concrete class.
- Irrespective of curing parameters, steel fiber reinforced concrete specimens were found to be higher than plain concrete mixtures in flexural tests, as expected. However, the differences between steel fiber reinforced and control mixtures were more pronounced in air and water curing parameters. Research advokates that steel fiber volume fraction and aspect ratio should be also highly considered in the case of steam curing and flexural load exposure.

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