

Going Beyond ACI 332: Commercial / Residential Enhanced Durability Concrete: Phase III The Effect of Limited Curing

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ABSTRACT

An absence or shortened amount of curing time for Portland cement concrete can reduce the potential degree of hydration in that concrete. Adequate curing can increase the potential for hydration, the chemical reaction between cement and water, and thus potentially increase the amount of hydration products. Hydration products not only increase strength, they also occupy the void space left by water used for hydration, creating a less permeable concrete matrix. Through these mechanisms, curing can increase both the strength and durability.

Curing concrete is often overlooked in practice due to its time-consuming process. Although the curing process can potentially slow down the progress of a project, it is crucial for the strength and durability development of concrete. Using a variety of common mixes (commercial 3500, commercial ACI, and CRED) and exposing them to limited various amounts of curing, the objective of this research is show how curing effects 28-day hardened properties.

Six batches of each mixture were used. Sixteen four-inch by eight-inch cylinders were cast from each batch. The cylinders from each batch were divided into four sets of four and each cured for a different length of time (0, 3, 7, and 14 days). Surface resistivity, compressive strength, and split tensile strength were determined at 28 days. The effects of extended amounts of curing increased the benefits of strength and durability properties in 38 out of 54 instances.

The compressive strength yielded the most improvement due to longer amounts of immersion curing, however split tensile and surface resistivity also had improvements in results based on curing time.

INTRODUCTION AND LITERATURE REVIEW

The process required to adequately cure concrete can be seen by many contractors as overwhelming or not worth the time and money. Common curing methods such as water ponding and the installation of wetted burlap, both for extended amounts of time, can stall the progress of a project and lead to scheduling problems for the remainder of the project. However, the process of curing concrete ensures the adequate strength development and promotion of durability characteristics (1). A concrete's strength is undoubtedly an important characteristic and is a main describing factor in its production, while the durability of a concrete determines how long that concrete's service life will be. An absence or shortened amount of time allowed for curing can lead to a decrease in both the strength and durability in concrete (2).

The introduction of external water after a concrete's final set provides moisture that can be used to keep the relative humidity (RH) of the concrete's matrix high and provide extra water to further promote the hydration of Portland cement (2). The longer this external water is present, the more opportunity the concrete has to reach a higher degree of hydration. Hydration products

take the place of the space previously occupied by the mixing water, so this promotion of hydration leads to more products being available to occupy what would have been permeable pore space, making the concrete stronger and less susceptible to harmful chloride ion penetration (3). Chloride ion penetration and sorptivity are durability problems in concrete that can lessen the service life of concrete and have been seen to be higher with concrete being only air cured (4).

An absence of external water after a concrete's final set, or air cured, has been seen in studies, such as a comparative study by Goel, to cause a lesser compressive and tensile strength than a concrete that has been cured via water immersion or under plastic film. This decrease in strength properties was seen in early age (3-7 days) as well as late age (28-56 days) testing, the latter of which produced the biggest difference due to the higher degree of hydration from the immersion groups (5). According to a study by Senbetta, a poorly cured concrete contained a chloride ion concentration of nearly 50% greater than a concrete that was well cured (6). This characteristic can lead to severe durability concerns for a concrete and lead to a shortened service life.

MATERIALS AND PROCEDURE

The materials used in this experiment are shown in Table 1, Column 1. The three mixes chosen to be used in this study have been used in two previous phases of research and are meant to represent a spectrum of low to high end performance based off of strength and durability characteristics. This spectrum is displayed left to right across the top of Table 1. The percent substitution of Class F fly ash in CRED is still beyond the maximum percentage allowed by ACI 332 for concrete subjected to RF3 and RF4 exposure classes, as it was in Phases I and II (8).

Table 1. Materials Used

Materials	Commercial 3500-psi	Commercial ACI 332	CRED
Type I/II PC, (lbs/CY)	375	451	312
Class F Fly Ash, (lbs/CY)	0	0	187.2
Class C Fly Ash, (lbs/CY)	1.5	113	0
Metakaolin, (lbs/CY)	0	0	20.8
No. 57 Stone, (SSD lbs/CY)	1816	1854	1911
River Sand, (SSD lbs/CY)	1281	1217	1252
Water, (lbs/CY)	250	250	203
Design Percent Air	6	5	6
Air Entrainer, (oz/cwt)	1.1	1.1	0.6
Mid-Range Water Reducer (oz/cwt)	4.2	7.4	8.8
High-Range Water Reducer (oz/cwt)	0.0	0.0	7.3

Six 1.06-cubic foot batches of each mixture were made with each batch consisting of sixteen four-inch by eight-inch cylinders. Sets of four cylinders within each batch were subjected to a certain amount of immersion curing time, namely 0, 3, 7 and 14 days. The lime-water immersion curing conforms to ASTM C192 specifications (9). Once the sets of cylinders had reached their prescribed amount of curing, they were removed from the immersion tank and left to air cure at room temperature. This curing schedule can be seen in Table 2.

Table 2. Type of Curing Leading Up to Age

Cylinder IDs	Age (days)					
	0 to 1	1 to 3	3 to 7	7 to 14	14 to 26	26 to 28
1-4	Mold	Air	Air	Air	Air	Immersion
5-8	Mold	Immersion	Air	Air	Air	Immersion
9-12	Mold	Immersion	Immersion	Air	Air	Immersion
13-16	Mold	Immersion	Immersion	Immersion	Air	Immersion

At 28 days, three out of four cylinders of each set were tested for chloride ion penetration via surface resistivity (SR). In order to conform to SR's test method, AASHTO T358-17, of testing saturated cylinders, every cylinder was placed back into the curing tank 48 hours prior to testing (10). This was done so as not to provide any additional curing as well as to provide moisture for adequate testing. Compressive strength and tensile strength were also tested at 28 days, directly after SR had taken place due to its non-destructive nature. Two cylinders of each set were tested in compression, and the other two were tested in tensile. Compressive strength

was tested in accordance to ASTM C39, and tensile strength was tested in accordance to ASTM C496 (11, 12).

RESULTS

The results for SR of each mixture at each curing age is shown in Table 3. Tables 4 and 5 display the results for compressive strength and tensile strength, respectively.

Table 3. 28-day SR Results, kilohm-cm

Mixture	Curing Age (days)	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Batch 6	Mean	Range
Commercial 13500	0	6.7	6.4	6.8	7.0	6.7	6.0	6.6	3.3
	3	7.2	7.3	7.9	7.7	7.6	6.8	7.4	3.7
	7	8.2	8.2	8.4	8.3	7.7	7.8	8.1	4.1
	14	8.8	8.6	8.6	8.4	8.1	8.2	8.5	4.2
Commercial 1ACI	0	8.2	7.8	7.0	8.7	8.5	8.4	8.1	1.7
	3	8.7	8.6	7.7	7.3	8.7	8.7	8.3	1.4
	7	8.6	7.8	7.6	7.1	8.4	8.6	8.0	1.5
	14	8.9	8.3	7.5	9.0	8.9	9.3	8.7	1.8
CRED	0	20.1	20.3	20.6	19.9	20.3	19.7	20.2	0.9
	3	19.9	20.5	19.8	19.2	20.3	19.6	19.9	1.3
	7	20.4	21.9	21.0	20.7	21.9	21.4	21.2	1.5
	14	22.2	22.3	22.3	21.5	21.9	22.5	22.1	1.0

Table 4. 28-day Compressive Strength Results, psi

Mixture	Curing Age (days)	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Batch 6	Mean	Range
Commercial 13500	0	1960	1910	2100	2150	2300	2050	2078	390
	3	2350	2400	2590	2590	2640	2480	2508	290
	7	2670	2920	2790	2790	2780	2740	2782	250
	14	3000	3000	3050	3040	2800	2940	2972	250
Commercial 1ACI	0	2720	2620	2750	2890	2890	2790	2777	270
	3	3080	3060	3390	3220	3190	3150	3182	330
	7	3470	3480	3720	3450	3530	3370	3503	350
	14	3620	3560	3720	3590	3520	3610	3603	200
CRED	0	3280	3580	3650	3780	3740	3730	3627	500
	3	3710	3830	4040	3920	3980	4140	3937	430
	7	4100	4350	4380	4370	4300	4410	4318	310
	14	4250	4340	4470	4550	4420	4710	4457	460

Table 5. 28-day Splitting Tensile Strength Results, psi

Mixture	Curing Age (days)	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Batch 6	Mean	Range
Commercial 13500	0	235	220	235	215	255	215	229	40
	3	290	290	260	290	295	270	283	35
	7	320	320	280	305	310	280	303	40
	14	290	315	300	305	325	335	312	45
Commercial 1ACI	0	300	280	310	305	305	300	300	30
	3	350	300	350	345	340	345	338	50
	7	315	335	340	360	345	335	338	45
	14	370	385	345	370	370	340	363	45
CRED	0	340	345	355	325	360	315	340	45
	3	345	375	345	325	415	355	360	90

	7	415	375	365	385	380	335	376	80
	14	400	400	400	415	390	390	399	25

QUALITY OF RESULTS

Tables 6, 7, and 8 show the comparison of actual and allowable ranges for each hardened state test. The allowable ranges were calculated via multiplying the mean result of each batch by a factor for maximum acceptable range from ASTM C670 that depends on the number of test results, as well as a coefficient of variation factor (COV) from each test's individual test method criteria (13). Note that the test method for split tensile strength, ASTM C496, does not include a COV factor for four-inch by eight-inch cylinders, however it does recommend a factor for six-inch by twelve-inch cylinders (12). This recommended factor was used in this quality analysis in order to provide a means of check on the ranges of the split tensile results.

The red shaded cells in Tables 6, 7, and 8 represent instances when the range obtained exceeded the allowable range. Green shaded cells represent instances when the range obtained was lower than the upper limit set by the allowable range.

Table 6. Comparison of All Mixture's SR Ranges to Allowable Ranges

Curing Age (days)	Commercial 3500		Commercial ACI		CRED	
	Range (kilohm-cm)	Allowable Range (kilohm-cm)	Range (kilohm-cm)	Allowable Range (kilohm-cm)	Range (kilohm-cm)	Allowable Range (kilohm-cm)
0	1	3.3	1.7	4.1	0.9	10.1
3	1.1	3.7	1.4	4.1	1.3	9.9
7	0.7	4.1	1.5	4	1.5	10.6
14	0.7	4.2	1.8	4.3	1	11.1

Table 7. Comparison of All Mixture's Compressive Strength Ranges to Allowable Ranges

Curing Age (days)	Commercial 3500		Commercial ACI		CRED	
	Range (psi)	Allowable Range (psi)	Range (psi)	Allowable Range (psi)	Range (psi)	Allowable Range (psi)
0	390	266	270	355	500	464
3	290	321	330	407	430	504
7	250	356	350	448	310	553
14	250	380	200	461	460	571

Table 8. Comparison of All Mixture’s Tensile Strength Ranges to Allowable Ranges

Curing Age (days)	Commercial 3500		Commercial ACI		CRED	
	Range (psi)	Allowable Range (psi)	Range (psi)	Allowable Range (psi)	Range (psi)	Allowable Range (psi)
0	40	45.8	30	60	45	68
3	35	56.5	50	67.7	90	72
7	40	60.5	45	67.7	80	75.2
14	45	62.3	45	72.7	25	79.8

Four out of thirty-six cases across all mixtures and tests are seen to have an actual range greater than the allowable range. Commercial 3500 and CRED with zero days of immersion curing experienced one batch having lower than normal compressive breaks. CRED with three and seven days of immersion curing experienced singular batches having higher than normal tensile strengths for their curing age. This is thought to be a symptom of sample size; however, the exact cause is unknown but considered not to be a problem.

ANALYSIS OF RESULTS

A statistical analysis of the hardened properties results for each mixture was conducted in order to determine which mix performed better with a certain duration of curing time. A statistical t-test with the assumption of unequal variances was conducted in order to accomplish this. When the absolute value of the calculated t-statistic was found to be less than the critical t-value at the corresponding degree of freedom, the results corresponding to this specific comparison were deemed to be not statistically different (NSD). When the absolute value of the calculated t-statistic was found to be greater than the critical t-value at the corresponding degree of freedom, the results corresponding to this specific comparison were deemed to be statistically significantly different (SSD). Once a comparison is deemed SSD, a closer look at the compared mean property values is required to declare which is superior or inferior.

The primary objective of this research involves comparing the results of different ages of curing within the same mixture as well as showing how different immersion curing periods affect the hardened property results. These comparisons are shown in Tables 9, 10, and 11. A secondary objective involves comparing results from the same curing age but between the three different mixes, which shows how each mixture compares to each other under the same limited curing conditions. These comparisons are shown in Tables 12, 13, and 14.

All mixtures in this study have been used in previous studies and were chosen for this experiment to represent a range of poorest to best performing (Commercial 3500, Commercial ACI, CRED, respectfully). It is through research highlighted in the literature review that the

hypothesis of samples being cured via immersion longer will perform better than samples that have not been cured via immersion for as long as that sample can be used. For Tables 9 through 12, green shaded cells represent an instance when the comparison is SSD and the result which has been immersion cured for the smaller period of time is inferior. The percent difference in means of the comparison is shown in these tables as well. Orange shaded cells represent an instance when the comparison is NSD. For Tables 13 through 15, green shaded cells represent an instance when the lower-ranking mix is SSD and inferior to the higher-ranking mix at that level of curing age. The percent difference in means of the comparison is shown in these tables as well. Orange shaded cells represent an instance when the comparison is NSD.

Table 9. Statistical Comparison of SR Results Within Each Mixture

Comparison	Commercial 3500		Commercial ACI		CRED	
0 Days vs 3 Days	Inferior	-12.4%	NSD		NSD	
0 Days vs 7 Days	Inferior	-22.7%	NSD		Inferior	-5.3%
0 Days vs 14 Days	Inferior	-28.0%	NSD		Inferior	-9.8%
3 Days vs 7 Days	Inferior	-9.2%	NSD		Inferior	-6.7%
3 Days vs 14 Days	Inferior	-13.9%	NSD		Inferior	-11.2%
7 Days vs 14 Days	NSD		NSD		Inferior	-4.2%

Table 10. Statistical Comparison of Compressive Strength Results Within Each Mixture

Comparison	Commercial 3500		Commercial ACI		CRED	
0 Days vs 3 Days	Inferior	-20.7%	Inferior	-14.6%	Inferior	-8.50%
0 Days vs 7 Days	Inferior	-33.8%	Inferior	-26.2%	Inferior	-19.10%
0 Days vs 14 Days	Inferior	-43.0%	Inferior	-29.8%	Inferior	-22.90%
3 Days vs 7 Days	Inferior	-10.9%	Inferior	-10.1%	Inferior	-9.70%
3 Days vs 14 Days	Inferior	-18.5%	Inferior	-13.3%	Inferior	-13.20%

7 Days vs 14 Days	Inferior	-6.8%	NSD	NSD
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Table 11. Statistical Comparison of Tensile Strength Results Within Each Mixture

Comparison	Commercial 3500		Commercial ACI		CRED	
	0 Days vs 3 Days	Inferior	-23.3%	Inferior	-12.8%	NSD
0 Days vs 7 Days	Inferior	-32.0%	Inferior	-12.8%	Inferior	-10.50%
0 Days vs 14 Days	Inferior	-36.0%	Inferior	-21.1%	Inferior	-17.40%
3 Days vs 7 Days	NSD		NSD		NSD	
3 Days vs 14 Days	Inferior	-10.3%	Inferior	-7.4%	Inferior	-10.90%
7 Days vs 14 Days	NSD		Inferior	-7.4%	NSD	

Table 12. Statistical Comparison of SR Results Within Curing Ages

Comparison	Curing Age (days)							
	0		3		7		14	
Commercial 3500 vs Commercial ACI	Inferior _r	-22.7%	Inferior _r	-11.7%	NSD		NSD	
Commercial 3500 vs CRED	Inferior _r	-205.3%	Inferior _r	-168.1%	Inferior _r	-161.9%	Inferior _r	-161.7%
Commercial ACI vs CRED	Inferior _r	-148.8%	Inferior _r	-140.0%	Inferior _r	-164.7%	Inferior _r	-155.7%

Table 13. Statistical Comparison of Compressive Strength Results Within Curing Ages

Comparison	Curing Age (days)							
	0		3		7		14	
Commercial 3500 vs Commercial ACI	Inferior _r	-33.6%	Inferior _r	-26.8%	Inferior _r	-25.9%	Inferior _r	-21.3%

Commercial 3500 vs CRED	Inferior	-74.5%	Inferior	-56.9%	Inferior	-55.2%	Inferior	-50.0%
Commercial ACI vs CRED	Inferior	-30.6%	Inferior	-23.7%	Inferior	-23.3%	Inferior	-23.7%

Table 14. Statistical Comparison of Tensile Strength Results Within Curing Ages

Comparison	Curing Age (days)							
	0		3		7		14	
Commercial 3500 vs Commercial ACI	Inferior	-30.9%	Inferior	-19.8%	Inferior	-11.8%	Inferior	-16.6%
Commercial 3500 vs CRED	Inferior	-48.4%	Inferior	-27.4%	Inferior	-24.2%	Inferior	-28.1%
Commercial ACI vs CRED	Inferior	-13.3%	NSD		Inferior	-11.1%	Inferior	-9.9%

DISCUSSION

The effect of limiting the curing time a concrete can go through in early stages dampens its ability to promote strength and durability characteristics, as seen by the previous tables. Not allowing excess water to enter the concrete's matrix after final set in order to increase both the rate and degree of hydration decreases the amount of strength gaining hydration product, calcium silica hydrate (CSH). With less CSH comes less strength bonds and more permeable pore space where these bonds would have taken place.

When examining the sole effect of curing time, as is done in Tables 9 through 11, it is seen that SR responded better to curing time in the commercial 3500 and CRED mixes than the commercial ACI. This could possibly be attributed to the mix design, as ACI has a higher amount of Portland cement than the other mixes, giving it much more opportunity to start making partial bonds through hydration and providing less permeable pore space. Commercial 3500 and CRED both responded well to SR in terms of immersion curing age, as 5 out of 6 cases in both mixtures proved the higher curing age to be beneficial.

The effect of providing more curing time had the greatest impact on compressive strength, as seen in Table 10. The commercial 3500 mixture's results indicated that every instance of comparison shows more immersion curing time leads to an SSD and higher compressive strength than those with less immersion curing time. Commercial ACI and CRED both experienced 5 out of 6 cases where more immersion curing time lead to an SSD and higher compressive strength as well.

Tensile strength performed well in both commercial 3500 and commercial ACI, with more curing time leading to SSD and higher tensile strengths in 4 and 5 out of 6 cases, respectfully. The CRED mixture seen split responses, with 3 out of 6 comparisons showing that an extended amount of immersion curing time caused SSD and higher tensile strengths than those with less immersion curing time.

The analysis shown in Tables 12 through 14 reaffirm the hierarchy of the mixtures shown in phase one of this research.

Figures 1 and 2 display how an increase in the amount of time a concrete is allowed to cure leads to higher strength and durability results.

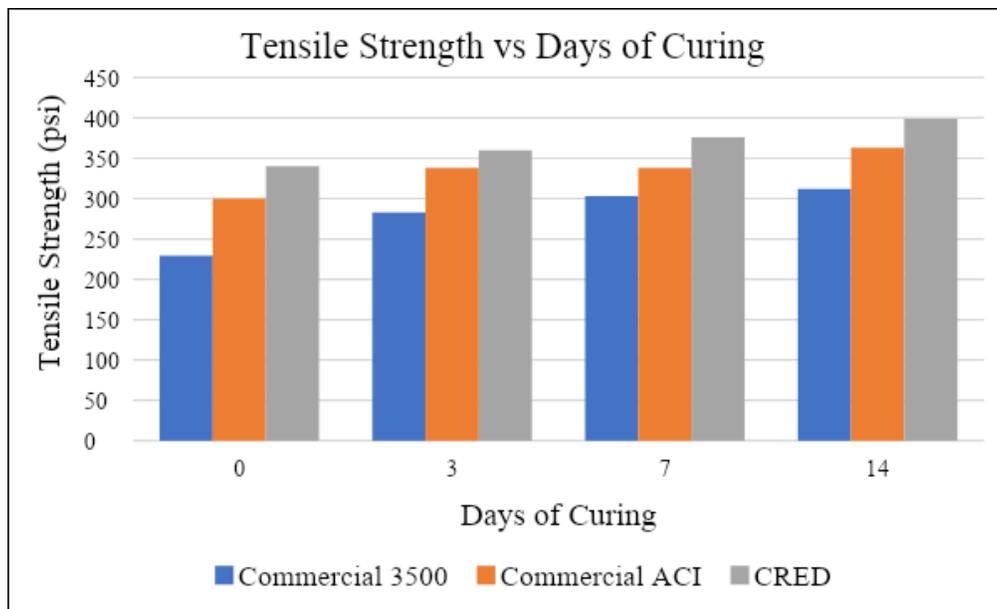
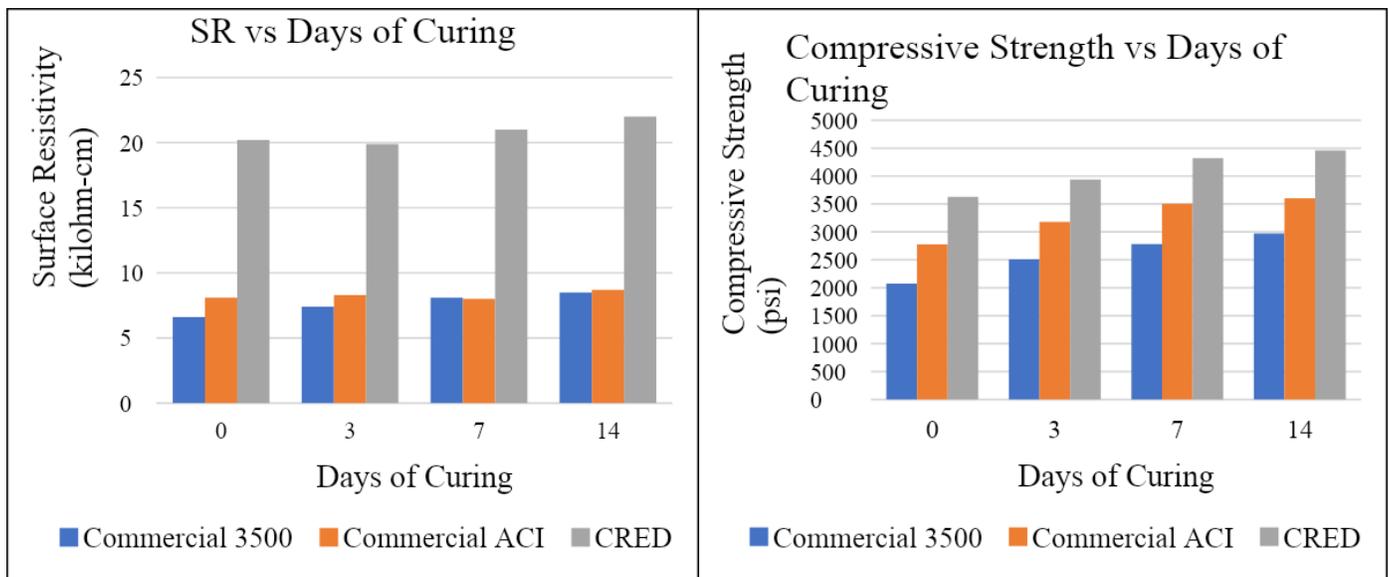


Figure 1 (Left) displays the smaller amount of change seen in SR results when considering longer amounts of immersion curing time. This is due in part to the smaller value in number of SR when compared to larger numbers such as compressive or tensile strength. Figure 1 (Right) and Figure 2 provide a good visual on the effects that extended curing time has on strength development. While the effects appear more prominent for compressive strength, tensile strength also has a similar strength development relationship.

CONCLUSIONS

Using three mixtures that are meant to represent a broad spectrum of commercial and residential concrete and subjecting them to four different time periods of immersion curing, it can be concluded that:

- More immersion curing time can benefit both strength and durability properties.
- If using the lower end of the commercial and residential concrete spectrum, which could be considered objectionable, simply curing for three days instead of not curing at all could lead to increase in compressive strength of up to 20%.
- Using a concrete on the high end of the commercial and residential spectrum, such as CRED, increases the resistance to chloride ion permeability, thus increasing the durability of the concrete without regard to the amount of immersion curing time.

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