Concrete Mix Design Study

Final Report

HP&R Project No. 5277

by

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16. Abstract

This study investigates several aspects of concrete mix design. The varibility of compressive strength, slump and air content from batch to batch is examined. The effect of increasing the sand content per cubic yard of concrete on the compressive strength is studied with another series of laboratory batches. Finally, the effect of the maximum coarse aggregate size on compressive strength is evaluated with a third set of laboratory batches.

The differences between the mean compressive strength of batches were evaluated using the Student 1 statistic. Some of the findings were:

- Variability in average 28-day compressive strength between laboratory batches of the same design is very low.
- The average 28-day compressive strength of concrete made with a 10% increase in the sand content is higher than that of concrete made with standard mix proportions. The workability of the former as measured by the slump is lower.
- The average 28-day compressive strength of concrete made with 3/4" maximum size aggregate is significantly higher than concrete made with 1 1/2" maximum size aggregate.

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1.0 INTRODUCTION

1.1 Background

Proportioning and testing of concrete mixtures has followed certain procedures within the Oregon State Highway Division. As part of the process some assumptions have been accepted but were never examined for local materials and equipment.

The Highway Division routinely uses small trial batches in the laboratory to evaluate and compare various mix designs. We assume that a single batch will adequately represent any particular mixture but repeatability of test results from batch to batch had not been confirmed with the equipment and procedures used here.

Currently, cylinders are capped with sulfur mortar for compression testing. Capping systems using neoprene pads are available and do meet AASHTO criteria. With neoprene caps the hazards associated with handling the molten sulfur can be eliminated. A previous unpublished study by the Division showed that test results were sometimes erratic with the neoprene caps.

The mix design procedure used by the Materials Section is basically the ACI method described in ACI 211 with modifications to coarse aggregate tables and to the estimated water content table. In recent years it was standard practice to increase the amount of sand in mixes by decreasing the amount of coarse aggregate originally estimated from the design procedure. The practice was established because of complaints from contractors about the harshness of standard mixes. Although trial batches did verify that such adjusted mixes could provide adequate compressive strength, no comparison with standard mix proportions were made. The effect of such adjustments on compressive strength and workability was not known.

Specifications for bridge deck concrete and other structures require a nominal maximum size aggregate of 1 1/2". For most other concrete a 3/4" maximum nominal aggregate size is permitted. An earlier study showed that equivalent mixtures with the 1 1/2" aggregate will have a lower compressive strength than the 3/4" mix. However, those tests were performed with a non-air entrained concrete and nearly all concrete placed on OSHD projects is air-entrained. It is not known whether the results of the earlier study would apply to air-entrained concrete.

1.2 Objectives and Scope

The first objective was to determine if test results would be repeated from batch to batch when the mix proportions for each batch are the same. At the same time a comparison between sulfur capped cylinders and neoprene capped cylinders would be made. The next objective was to determine if the compressive strength and workability of a mix changes when the relative amount of coarse aggregate and sand is changed. Finally, we wished to determine if changing the maximum coarse aggregate size in a mix from 1 1/2 inch to 3/4 inch will affect its compressive strength. The study was divided into four tasks outlined below.

Task A evaluates the repeatability of laboratory trial batches. Several 1 to 1.5 cubic foot batches were prepared according to AASHTO T126 in a laboratory mixer. Standard tests were run on the fresh concrete and cylinders were cast from each batch. The cylinders were tested for compressive strength. The variations in test results between similar batches were evaluated. In addition, the compressive strength of sulfur-capped versus neoprene capped cylinders was compared.

Task B was a literature review to find pertinent studies or research on Tasks C and D. Literature available from the Materials Library and the Research Unit library was studied.

Task C evaluates the effect on a mixture's compressive strength of reducing the coarse aggregate by 10%. A mix was designed according to OSHD TM 718, Concrete Mix Design. Several small laboratory batches were mixed using the design and tested for compressive strength. The coarse aggregate content of the design was reduced 10% by weight with a corresponding increase in sand to maintain the yield. A second series of batches was prepared and tested using the modified design. The results were analyzed for statistically significant differences in compressive strength.

Task D is the evaluation of the effect of coarse aggregate size on compressive strength. Mixes were designed with both 1 1/2" maximum nominal aggregate size and 3/4" maximum nominal aggregate size. Cement and water contents were the same. Several laboratory batches were prepared with each mix design. The fresh concrete was tested and cylinders were cast. The cylinders were tested for compressive strength and the results of the two mixes were compared statistically.

2.0 TASK A EVALUATE TRIAL BATCH REPRODUCIBILITY

2.1 Background

Mix proportions for a particular concrete are calculated from aggregate test data and from tables in the mix design procedures. A trial batch is then prepared to verify performance of the mix. If trial batch test results meet established criteria, verification of the mix design is complete. A successful trial batch was rarely repeated so batch to batch variations with the same materials and proportions were unknown.

The type of caps used on the cylinders for compressive strength testing has been the subject of several evaluations. The Materials Section has used molten sulfur capping for many years but the molten sulfur is somewhat hazardous. Therefore, a capping system using neoprene pads has been tested. Testing to date has shown erratic results when the neoprene system is used and usually lower compressive strengths than sulfur capped cylinders.

2.2 Purpose

To evaluate the precision and repeatability of the test results from identical batches of concrete prepared in the laboratory. Also to compare compressive strength test results of cylinders capped with sulfur mortar and cylinders capped with a neoprene capping system when both are prepared from the same batch.

2.3 Scope

Five trial batches were prepared using a Class 3000 mix with a cement content of 517 lbs. per cubic yard and a water to cement ratio of 0.47. Another five trial batches were prepared using a Class 5000 mix with a cement content of 658 lbs. per cubic yard and a water to cement ratio of 0.40. Aggregates from the same source and with the same grading were used in all batches. The type and brand of cement and Air Entraining Agent were also the same. Each batch was mixed according to AASHTO T126 and tested for slump, air content and unit weight. Cylinders were cast, cured for 28 days according to AASHTO T23 and tested for compressive strength according to AASHTO T22. Four cylinders from each batch were capped with a sulfur compound and another four were tested with neoprene caps. Test results were compared among the trial batches for each mix design and analyzed.

2.4 Test Procedure

2.4.1 Test Equipment

Drum mixer rated at 2 cu. ft. capacity

Mortar mixing pan – for remixing concrete

Standard metal slump cone

1/4 cu. ft. White pressure air meter

Single-Use 6" x 12" plastic cylinder molds

2.4.2 Materials

Coarse aggregate	Local round river gravel 1" – #4
Fine aggregate	Local natural sand
Cement	Calaveras Type 1, all the same lot
Air Entraining	Master Builders MB-VR
Water	City water
Capping	Atlas Vitrobond Sulfur mortar
	Sure Cure Neoprene caps (Standard)

2.4.3 Aggregate Preparation

The coarse and fine aggregate did comply with Highway Division specifications for soundness, durability and deleterious substances. The specific gravity, absorption and the unit weight of the aggregates was determined. This information was used in designing the mix proportions.

The coarse aggregate was oven dried then separated into 3/4", 1/2", 3/8", 1/4" and #4 sizes. Coarse aggregate gradation was established by using the ideal grading from the Fuller maximum density curve for 1" to #4 material. The individual sizes were recombined for each batch to meet this grading. The coarse aggregate was weighed out dry then soaked in water overnight.

Sand was prepared by bringing it to a moisture content above the Saturated Surface Dry condition then putting it into sealed buckets until the batch was prepared. A sample was taken the day before batching and used to determine sand moisture content.

2.4.4 Batching Mixing and Testing

Batching and mixing complied with the procedure in AASHTO T 126. Excess water was drained from the coarse aggregate and it was weighed again. Free moisture was calculated and subtracted from mixing water. The sand free moisture was determined from total moisture content. Coarse aggregate and some water with the air entraining agent was added to the mixer. The damp sand was added to the mixer. The mixer was operated for 30 seconds then the cement and final portion of the water was added. The mixture was mixed for 3 minutes, rested for 2 minutes and mixed for the final 2 minutes. The concrete was dumped from the drum mixer into a mortar pan and mixed with shovels for another minute. The concrete was tested for slump, unit weight and air content when the mixing was done.

2.4.5 Cylinder Preparation and Testing

When the other tests were completed the sample was remixed before casting cylinders. Cylinders were consolidated by rodding. All cylinders from each batch were cast at the same time. The first lift was added to each cylinder then all were rodded and tapped. Then the second lift was added, etc. After the top surface was finished plastic lids were placed on the cylinders, they were covered with wet burlap and left in a 60-80 degree environment for the next 24-hrs. The following day the cylinders were removed from the molds. Those designated for sulfur caps were capped and all were stored in the moist room until test.

When the 28 day curing period was complete the cylinders were removed from the moist room, their diameter was measured and they were tested for compressive strength according to AASHTO T22. The cylinders without sulfur caps were tested with medium softness(standard) neoprene caps. The compressive strength results are shown in Tables 1 and 2. Table 1 shows the results for the Class 3000 mix while Table 2 shows results for the Class 5000 mix.

2.5 Analysis of Results

The precision statement for AASHTO Test Method T 126 Making and Curing Concrete Test Specimens in the Laboratory is a single operator Standard Deviation of 0.7 inches for slump, 0.3% for air content and 0.9 lbs/cu. ft. for unit weight. The standard deviation for compressive strength of cylinders tested at 7 days is 203 psi. The data used to determine these values is from concrete with very low air contents so it might be reasonable to expect greater variation at the higher air contents in these trial batches.

The T 126 precison statement also states that test results on two trial batches made in the same laboratory should not differ by more than 2.0 inches slump, 0.8% air content, 2.5 lbs./cu. ft. in unit weight and 574 psi for 7 day compressive strength.

The precision statement is used to analyze and evaluate test results from the trial batches conducted under Task A. Since compressive strength will be the most important measurement for Tasks C and D, the strength results from Task A batches are analyzed first.

2.5.1 Compressive Strength

The test results for the Class 3000 mix design are shown in Table 1. The average 28-day strength of the sulfur capped cylinders ranged from 3660 psi for batch #35 to 3920 psi for batch #42, a range of 260 psi. The neoprene capped cylinders averaged from 2980 psi for batch #38 to 3960 psi for batch #42, a range of 980 psi. The maximum difference between any two batches with sulfur capped cylinders was well within the 574 psi from the precision statement. The neoprene capped cylinders had a maximum range which exceeded the precision limits.

The average strength of all four batches was 3825 psi (sulfur caps) and between batch standard deviation was 121. This is well within the single operator precision limits. In addition, according to ACI 214-77 Table 3.5 a standard deviation of 121 indicates excellent control. For the neoprene capped cylinders the average of the four sets was 3425 psi with a standard deviation of 452. This amount of variability might be expected on projects with poor control standards (ACI 214).

The sulfur capped cylinders achieved a higher strength in three of the four batches. However, one set of neoprene capped cylinders had the highest average strength of all eight sets. The between batch variation was also much lower with sulfur capped cylinders.

Results for the Class 5000 mixture are in Table 2. The average 28-day strengths of the sulfur capped cylinders ranged from 4300 psi for batch #55 to 4660 psi for batch #51, a range of 360 psi. This range falls well within the AASHTO T 126 precision limits for 7-day compressive strength. The average 28-day strength of the neoprene capped cylinders ranged from 4120 psi in batch #55 to 4520 psi for batch #45, a range of 400 psi. This is also within the precision limits.

The average strength of all neoprene capped cylinders was 4290 psi. The standard deviation was 184, a great improvement over the variability of strengths from neoprene capped cylinders with the other mix. Five sets of sulfur capped cylinders average 4510 psi with a between batch standard deviation of 156. Standard deviations in both cases were well within the precision limits. In both cases this indicates Excellent control according to the ACI 214 standard. The strength achieved by the neoprene capped cylinders was lower in all five batches although the variations in strength were much less than the Class 3000 mixture.

2.5.2 Slump, Air Content and Unit Weight

Test results for the two different mixes are reported on Tables 1 and 2. Range and standard deviations for slump, air content and unit weight are also on the Tables. The differences between test results from any two batches in each series are within the limits set in the precision statement. Also, the standard deviations for each type of test in each series is within the single operator standard deviations given in the precision statement.

TABLE 1

TASK A TRIAL BATCH REPRODUCIBILITY RESULTS

CLASS 3000

BATCH NO.	SLUMP (Inches)	AIR (%)	UNIT WEIGHT (lbs/cu ft)	AVERAGE 28-DAY COMPRESSIVE STRENGTH SULFUR (PSI)	NEOPRENE (PSI)	PERCENT DIFFERENCE
35	6.25	6.2	140.6	3660	3130	17%
38	6.00	6.0	141.8	3810	2980	28%
42	5.75	5.6	142.6	3910	3960	1%
43	6.75	5.9	141.8	3920	3630	8%
AVG	6.25	5.9	141.7	3825	3425	12%
RANGE	1.0	0.6	2.0	260	980	
STD. DEVIATION	0.4	0.3	0.8	121	452	
RATING (ACI 214)				EXCELLENT	POOR	

TABLE 2

TASK A TRIAL BATCH REPRODUCIBILITY RESULTS

CLASS 5000

BATCH NO.	SLUMP (Inches)	AIR (%)	UNIT WEIGHT (lbs/cu ft)	AVERAGE 28-DAY COMPRESSIVE STRENGTH SULFUR (PSI)	NEOPRENE (PSI)	PERCENT DIFFERENCE
44	5.25	5.1	142.4	4390	4190	5%
45	5.50	5.0	143.1	4560	4520	0%
50	6.00	5.0	143.1	4630	4170	11%
51	6.25	5.2	143.0	4660	4460	4%
55	5.25	4.4	144.5	4300	4120	4%
AVG	5.65	4.9	143.2	4510	4290	5%
RANGE	1.0	0.8	2.1	270	400	
STD. DEVIATION	0.5	0.3	0.8	156	184	
RATING (ACI 214)				EXCELLENT	EXCELLENT	

3.0 TASK B LITERATURE REVIEW

Prior to initiation of Laboratory studies for the Evaluation of Coarse Aggregate Factor (Task C) and the Effect of Coarse Aggregate Size (Task D), a literature study was conducted to obtain information about the two research topics. Of particular interest were the effect on concrete strength of varying ratios of coarse aggregate to sand and the effect on compressive strength of a larger maximum size coarse aggregate.

3.1 Coarse Aggregate Factor

3.1.1 General

The literature search turned up little information relating compressive strength directly to the relative amounts of coarse aggregate and sand in a concrete mixture. A short, unpublished study(1) was performed by the Materials Section in 1972 to compare the compressive strength, slump and water-cement ratio of mixes with varying proportions of coarse aggregate and sand. A series of laboratory batches was prepared with the same cement content but varying amounts of sand and coarse agggregate. The percent of sand to total aggregates varied from 23% to 48% in 5% increments. Test results showed increasing compressive strength as the percentage of sand increased but also an increase in the mix water needed to maintain a 3" slump. The compressive strength of the most sandy mix (48%) was more than 1000 psi above the least sandy mix (23%) while mix water increased by 18 lbs per cubic yard. There were no conclusions presented but in this study increasing the sand content did not reduce the compressive strengths of the mix.

General concrete texts(2,3,4) caution against using an excessive amount of sand in concrete mixes for several reasons. One is economy. Usually, coarse aggregate is less costly to produce than sand. Therefore, an economical mix has as much coarse aggregate as possible with only enough sand to provide workability. Secondly, the greater surface area of the sand requires more water to maintain workability of the concrete. Additional water will usually reduce compressive strength, increase permeability and increase shrinkage of the hardened concrete. But add too little sand and the mix is harsh and difficult to place and finish. One purpose of any mix design procedure is to balance the need to keep water content as low as possible yet create a mix which is sufficiently workable to place easily. There is no exact best ratio of sand to coarse aggregate. Usually a wide range of sand to coarse aggregate ratios could satisfy job requirements.

A principal difference between mix proportioning methods is in how the relative amounts of sand and coarse aggregate is determined. The method currently used in ACI 211 and in OSHD TM718 was developed by Talbot and Richard(5) and further refined by Goldbeck and Gray(6). The tables in the two mix design methods provide what we have called the "Coarse Aggregate Factor". This number is actually a ratio of coarse aggregate per unit volume of concrete and it provides an estimate for the amount of coarse aggregate to use in the mix. As noted earlier, ACI 211 does permit a reduction in coarse aggregate content to improve the workability of the mixture.

Another procedure is the Fineness Modulus Method originally developed by Duff Abrahms and subsequently modified by several different researchers(7). In this method a desired overall fineness for the combined coarse and fine aggregates is read from a table. The combined fineness modulus is affected by the cement content and the maximum size of the coarse aggregate. The two aggregates are then combined in the mix such that their combined fineness modulus equals that from the table. This method tends to produce a mix with slightly more sand than ACI 211 or OSHD TM 718 but not as much sand as the 10% reduction in coarse aggregate that ACI 211 would allow.

The Portland Cement Association Water-Cement Ratio method(8) for mix design does not predetermine the ratio of coarse aggregate to sand. Instead, coarse aggregates and sand are added to a trial batch until a workable mixture as judged by the technician is achieved. Then the weight of each aggregate on a per cubic yard basis is calculated. This method may yield similar proportions to ACI 211 or it may not, it will depend on the technician.

3.1.2 Conclusions drawn from literature study

The concrete mix design process involves balancing the requirements for workability, economy, strength and long term durability. Mix design methods will vary in the amount of coarse aggregate and sand recommended for a particular mix. This points out that there is no single best combination for a given set of materials. Too much sand in the mix will increase the mix water needed to provide a workable mixture. Increased water tends to reduce compressive strength and may increase permeability and shrinkage of the concrete. In general, it is desirable to keep the sand content low but the final criterion is the performance of the mix.

3.2 Effect of Coarse Aggregate Size on Concrete Strength

3.2.1 General

A study by Stanton Walker and Delmar Bloem "Effects of Aggregate Size on Properties of Concrete" (9) concluded that compressive strength of 6 sack air entrained mixes was equal whether 1 1/2" or 3/4" maximum size aggregates were used. However, when the cement content was increased to 8 sacks (752 lbs) the 3/4" mixes were stronger. They found that for all air-entrained concrete strength was reduced as maximum aggregate size was increased above 3/4 inch.

Cordon and Gillispie(10) also found a relationship between aggregate size and compressive strength for medium strength and high strength concretes. They tested mixes with maximum aggregate size ranging from No. 4 up to 3 inches and found that compressive strength decreased as the maximum aggregate size increased. The effect was most significant with mixes at a water–cement ratio of 0.40 and less dramatic but still significant at a water–cement ratio of 0.55.

A study was conducted by the Oregon State Highway Division(11) to determine if conclusions drawn from data reported by other agencies is applicable to concrete made with local materials. The report concluded that the coarse aggregate size requirements should be reduced from 1 1/2 inches to 3/4 inch. Results showed that with cement contents above 6 sacks (564 pounds) of cement per cubic yard the smaller maximum size aggregate gave higher strength. All the mixes in this study were non–air entrained.

3.2.2 Conclusions Drawn from Literature Study

It seems clear that smaller maximum aggregate sizes provide improved compressive strength at higher cement contents. The PCA book Design and Control of Concrete Mixtures states "For high compressive strength concrete (6000 psi plus) with a cement content exceeding 600 lb per cubic yard, the optimium maximum size is about 3/4 in."

The advantage to larger aggregate sizes is that less water and therefore less cement is required, making a more economical mix.

4.0 TASK C EVALUATE COARSE AGGREGATE FACTOR

4.1 Background

An important part of the concrete mix design process is to determine the relative amounts of coarse and fine aggregate for a mix. The workability, finishability, durability and the compressive strength of the concrete may be affected. In ACI 211.1, Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete a ratio from Table 6.3.6 (the coarse aggregate factor) is used to estimate the proper amount of coarse aggregate. This ratio is the volume of dry aggregate per unit volume of concrete. Values in the table range from 0.44 to 0.87 depending on the coarse aggregate size and the fineness of the sand. The ratio is multiplied by 27 then times the dry-rodded unit weight of the coarse aggregate to yield the dry weight of coarse aggregate per cubic yard of concrete.

Because the volume of cement, water and entrained air are determined earlier in the process, the amount of coarse aggregate directly affects the amount of the final ingredient – the sand. The coarse aggregate ratios in ACI 211 were determined from numerous test batches. They attempt to provide a workable mixture without an excessive amount of sand. For some placement situations mixtures designed by this method may be too harsh and rocky. Therefore, ACI 211.1 permits a 10% decrease in coarse aggregate content (and thus an increase in sand) to provide improved workability. There is a caution that the adjusted mix must be tested for strength, slump and water-cement ratio.

The Materials Section has used a modification of the ACI 211 table to estimate the amount of coarse aggregate for mix designs. It has been common practice to reduce coarse aggregate content in most mixes we designed to alleviate contractor complaints about workability. However, little has been done to examine the effects of reducing coarse aggregate content.

4.2 Purpose

To investigate the effects on compressive strength of reducing coarse aggregate content and increasing the sand content of a concrete mix.

4.3 Scope

Two mix designs were calculated for the same aggregate and the same cement content and water cement ratio. The first was designed in accordance with the tables in ACI 211. Table 6.3.6 "Volume of Coarse Aggregate per unit Volume of Concrete" was used to determine the weight of coarse aggregate. For the second design the coarse aggregate weight was reduced 10% and the volume was made up with additional sand.

Seven laboratory batches using standard mix proportions were prepared and tested for compressive strength. Five more laboratory batches were prepared and tested using the same design except that coarse aggregate was reduced by 10% in weight and sand content was increased to make up the volume.

4.4 Test Procedure

4.4.1 Equipment

Lancaster Pan Mixer of 1.75 cu. ft. capacity

Standard metal slump cone

1/4 cu. ft. White pressure air meter

Single use 6" x 12" plastic cylinder molds

4.4.2 Materials

Coarse aggregate	Local round river gravel 1" – #4
Fine Aggregate	Local natural river sand
Cement	Calaveras Type I (All same lot)

Air Entraining	Master Builders MB-VR
Water	City water

4.4.3 Aggregate Preparation

The coarse and fine aggregate did comply with Highway Division specifications for soundness, durability, and deleterious substances. The specific gravity, absorption and the unit weight of the aggregates was determined. This information was used in designing the mix proportions.

The coarse aggregate was oven dried then separated into 3/4", 1/2", 3/8", 1/4", and #4 sizes. Coarse aggregate grading was established by using the ideal grading from the Fuller maximum density curve for 1" to #4 material. The individual sizes were recombined for each batch to meet this grading. The coarse aggregate was weighed out dry then soaked in water overnight.

Sand was prepared by bringing it to a moisture content above the Saturated Surface Dry condition then putting it into sealed buckets until the batch was prepared. A sample was taken the day before batching and used to determine sand moisture content.

4.4.4 Batching, mixing and testing

Batching and mixing of the batches complied with the procedure in AASHTO T126. Excess water was drained from the coarse aggregate and it was weighed again. Free moisture was calculated and subtracted from mixing water. The sand free moisture was determined from total moisture content. Coarse aggregate and some water with the air entraining agent was added to the mixer. The damp sand was added to the mixer. The mixer was operated for 30 seconds then the cement and final portion of the water was added. The mixture was mixed for 3 minutes, rested for 2 minutes and mixed for a final 2 minutes. The mixture was remixed by hand in the pan. Tests for slump, unit weight and air content (pressure method) were performed when the mixing was completed.

4.4.5 Cylinder Preparation and Testing

Cylinders were consolidated by rodding. All four cylinders from each batch were cast at the same time. The first lift was placed in each mold then all were rodded and tapped. The second lift was placed in each mold, etc. The filled molds were covered with plastic lids provided with the cylinders then moved to the laboratory moist room for the initial cure period. The following day the cylinders were removed from the moist room, stripped of their molds, and capped with sulfur compund. They were then returned to the moist room until 28-days from mixing day.

After 28 days of curing the cylinder diameters were measured and the cylinders were tested for compressive strength according to AASHTO T 22. Test results are summarized in Table 3.

4.5 Analysis of Results

As shown in Table 3 the average compressive strength of the batches with the reduced coarse aggregate content was higher than the standard mix. To determine if there is a significant difference in compressive strength, analysis by Student t statistic was performed. Results are in Table 4. The p-value indicates the likelihood of the observed results if the hypothesis is true. Since the p-value is very small there is little likelihood that the mean strength of the two types of mixes is the same. The hypothesis is rejected and we can conclude that when the coarse aggregate is reduced and the sand is increased the compressive strength increases, at least if the water content is the same.

The batches with the increased sand content did on average have a lower slump. The slump of the normal batches averaged 4.9 inches while that of the increased sand batches averaged 4.2 inches. This follows the expected result that as sand content is increased, the water demand increases to maintain equal workability. In this case we did not increase the water to maintain equal slump. Perhaps if the water content had been increased to maintain a slump equal to the first set of batches the strengths would have been equal. This would be an area for further study.

The mixtures in this study did not have any type of water–reducing admixture. The reduction in workability caused by reducing the coarse aggregate and increasing the sand content may be counteracted with such an admixture. This also would be an area for further study.

Table 3

TASK C EVALUATE COARSE AGGREGATE FACTOR

A. Standard Mix Proportions as per ACI 211

BATCH NO.	SLUMP (Inches)	AIR (%)	UNIT WEIGHT (lbs/ft3)	W/C Ratio	Avg. 28-day Compressive Strength
61-88	4.50	4.7	144.7	0.43	4000
63-88	4.00	4.5	144.2	0.43	3910
64-88	4.00	4.6	144.2	0.43	4240
65-88	4.50	5.0	143.1	0.43	4210
66-88	5.50	4.9	143.2	0.43	4140
29-89	6.75	5.5	142.8	0.43	4320
34-89	5.00	4.8	143.9	0.43	3810
Averages	4.90	4.9	143.7		4090 psi
	Standard Deviation of Strength Tests				141

B. Coarse Aggregate reduced 10% by weight

BATCH NO.	SLUMP (Inches)	AIR (%)	UNIT WEIGHT (lbs/ft3)	W/C Ratio	Avg. 28-day Compressive Strength
67-88	3.25	4.8	143.9	0.43	4260
68-88	4.00	5.1	142.9	0.43	4210
69-88	4.50	5.2	143.0	0.43	4330
70-88	4.50	5.2	143.3	0.43	4380
71-88	4.50	5.2	142.5	0.43	4230
Averages	4.20	5.1	143.1		4280 psi
	Standard Deviation of Strength Tests				71

TABLE 4

TASK C EVALUATE COARSE AGGREGATE FACTOR

STATISTICAL ANALYSIS

HYPOTHESIS: There is no statistical difference in the average strength of concrete made from the two types of mixes.

Difference between the Means:	180
Pooled Standard Deviation:	115
Total Samples:	11
Calculated (t) Statistic:	2.729
p–Value:	0.05 – 0.02
p–Value:	between 0.05 and 0.02
CONCLUSION:	Hypothesis is rejected

5.0 TASK D EFFECT OF MAXIMUM COARSE AGGREGATE SIZE

5.1 Background

Current Oregon State Highway Division specifications require coarse aggregate with a nominal maximum size of 1 1/2 inches in concrete mixtures for bridge decks, some end panels and concrete paving. Most other structural elements may use a 1" or 3/4" maximum size aggregate. In 1991 over 50% of the cylinder sets which did not reach minimum specified strength were mixes for bridge decks or paving with 1 1/2" maximum size aggregate. Only 25% of the failures were 1" or 3/4" Class 3300 or 4000 mixes. The remainder were higher strength mixes specified at 5000 psi or greater. These figures indicate what many in the industry accept as fact; that mixes with 3/4" aggregate will have higher compressive strengths than equivalent mixes with 1 1/2" aggregate.

5.2 Purpose

To investigate the effects on compressive strength of using 3/4" nominal maximum size aggregate instead of a nominal maximum size of 1 1/2" in mixes with equal cement content.

5.3 Scope

Two mix designs were calculated using OSHD Test Method 718. One was designed with 1 1/2" maximum aggregate size and the other with a 3/4" maximum aggregate size. The cement content for both designs was 7 sacks (658 lbs) per cubic yard and the water/cement ratio was set at 0.38 for both. Four 1.5 cubic foot batches were prepared with each design.

Tests for slump, unit weight, air content and mix temperature were run on each batch. Four 6" x 12" cylinders were cast in single use plastic molds for each batch. The cylinders were cured in accordance with AASHTO T126 and tested at 28 days for compressive strength.

Test results were analyzed by comparing the average 28 day compressive strength of the 1 1/2" mixes with the average compressive strength of the 3/4" mixes. Test results are shown on Table 5.

5.4 Test Procedure

5.4.1 Test Equipment

Laboratory pan mixer 1.75 cu. ft. capacity

Standard metal slump cone

1/4 cu. ft. White pressure air meter

Single-use 6" x 12" plastic cylinder molds

5.4.2 Materials

Coarse aggregate	Local round river gravel 1" - #4 size
Fine aggregate	Local natural sand
Cement	Calaveras Type 1 (All the same lot)
Air Entraining	Master Builders MB-VR
Water	City Water

5.4.3 Aggregate preparation

The coarse and fine aggregate did comply with Highway Division specifications for soundness, durability, and deleterious substances. The specific gravity, absorption and the unit weight of the aggregates was determined. This information was used in designing the mix proportions.

The coarse aggregate was oven dried then separated into 3/4", 1/2", 3/8", 1/4", and #4 sizes. Coarse aggregate grading was established by using the ideal grading from the Fuller maximum density curve for 1" to #4 material. The individual sizes were recombined for each batch to meet this grading. The coarse aggregate was weighed out dry then soaked in water overnight.

Sand was prepared by bringing it to a moisture content above the Saturated Surface Dry condition then putting it into sealed buckets until the batch was prepared. A sample was taken the day before batching and used to determine sand moisture content.

5.4.4 Batching, Mixing and Testing

Batching and mixing of the batches complied with the procedure in AASHTO T126. Excess water was drained from the coarse aggregate and it was weighed again. Free moisture was calculated and subtracted from mixing water. The sand free moisture was determined from total moisture content. Coarse aggregate and some water with the air entraining agent was added to the mixer. The damp sand was added to the mixer. The mixer was operated for 30 seconds then the cement and final portion of the water was added. The mixture was mixed for 3 minutes, rested for 2 minutes and mixed for a final 2 minutes. The mixture was remixed by hand in the pan. Tests for slump, unit weight and air content (pressure method) were performed when the mixing was completed.

5.4.5 Cylinder Preparation and Testing

The cylinders were consolidated by rodding. All cylinders from each batch were cast at the same time. The first lift was added to each cylinder then all were rodded and tapped. Then the second lift was placed in each mold, etc. The filled molds were covered with the plastic lids provided with the cylinders and left to cure for 24–hours in a surrounding temperature of 60 to 80 degrees Farenheit. The following day the cylinders were stripped from their molds, capped with sulfur mortar and returned to the moist room for the additional curing.

After 28 days of curing the cylinder diameters were measured and the cylinders were tested for compressive strength according to AASHTO T22. Test results are shown in table 5.

5.5 Analysis of Results

Compressive strength results were very consistent from batch to batch within the two mix designs. As expected the average compressive strength of the 3/4" mix did exceed the average compressive strength of the 1 1/2" mixes. To determine if there is a significant difference in strength between the two types of mixes, analysis by Student t statistic was performed. Results are in Table 6. The very low p-value indicates there is little likelihood that the mean strength of the mixes is the same. The hypothesis is rejected.

Results of slump tests are interesting. It is evident that at equal water-cement ratios the slump of the 1 1/2" mixes is noticeably higher. If water were added to the 3/4" mix to match the slump of the 1 1/2" mix there might not be such a difference in compressive strengths. In situations where a low water-cement ratio is preferred for reasons other than compressive strength it appears that the mix with a larger size aggregate has an advantage. It can provide more workability for ease of placement at a lower water-cement ratio than a 3/4 inch mixture.

Table 5

TASK D EFFECT OF MAXIMUM COARSE AGGREGATE SIZE

A. Batches with 1 1/2" Maximum Size Aggregate

BATCH NO.	SLUMP (Inches)	AIR (%)	UNIT WEIGHT (lbs/ft3)	W/C RATIO	Avg. 28-day Compressive Strength
41-89	4.75	4.1%	145.8	0.38	3750
4-90	5.50	5.4%	143.9	0.38	3660
6-90	5.50	5.1%	144.3	0.38	3650
8-90	4.50	5.2%	143.5	0.38	3820
Averages	5.10	5.0	144.4		3720
	Standard Deviation of Strength Tests				80

B. Batches with 3/4" Maximum Size Aggregate

BATCH NO.	SLUMP (Inches)	AIR (%)	UNIT WEIGHT (lbs/ft3)	W/C RATIO	Avg. 28-day Compressive Strength
3-90	3.25	5.2%	144.7	0.38	4240
5-90	3.75	5.2%	143.4	0.38	4180
7-90	3.75	5.3%	143.9	0.38	4140
AVERAGE	3.60	5.2%	144.7		4190
	Standard Deviation of Strength Tests				50

TABLE 6

TASK D EFFECT OF MAXIMUM COARSE AGGREGATE SIZE

STATISTICAL ANALYSIS

HYPOTHESIS: There is no statistical difference in the average strength of concrete made from 1 1/2" aggregate and that made with 3/4" aggregate.

Difference between the Means:	470
Pooled Standard Deviation:	70
Total Samples:	7
Calculated (t) Statistic:	8.816
p–Value:	Less than .001

CONCLUSION: Hypothesis is rejected.

6.0 CONCLUSIONS

Conclusions resulting from this study include:

1) The repeatability of compressive strengths from batch to batch in this laboratory is excellent when the cylinders are capped with sulfur mortar.

2) Batch to batch repeatability of slump, air content and unit weight tests meets AASHTO limits for precision.

3) Compressive strength test results are lower and more variable when the cylinders are tested with a neoprene capping system.

4) Reducing the coarse aggregate content of a mixture and increasing the sand content by up to 10% by weight from the original estimates using ACI 211 does not have a detrimental effect on compressive strength. Test results showed increased compressive strength.

5) Increasing the sand content of a concrete mixture will reduce the slump of the mixture.

6) At a cement content of 7 sacks (658 lbs) per cubic yard, a concrete with 3/4 inch maximum size aggregate will produce higher compressive strengths than one with 1 1/2" maximum size aggregate when both are at the same water-cement ratio.

7.0 RECOMMENDATIONS FOR IMPLEMENTATION

Recommendations based on this study are:

1) Permit the use of concrete mix designs which have a reduced coarse aggregate content up to the 10% reduction permitted by ACI 211. The contractor must still demonstrate that the mix will have sufficient strength and will have a water content within specification limits.

2) Permit the use of 3/4 inch or 1 inch maximum size aggregate as an option in place of 1 1/2 inch maximum size aggregate currently required for bridge decks and culverts. Higher strengths can be achieved with the smaller aggregate so it may be appropriate to increase the specified compressive strength when smaller aggregate is used. The higher strength should improve wear resistance of the surface.

   This study also shows that a 3/4 inch aggregate mix will have less workability (lower slump) than an equivalent 1 1/2 inch mix. Since bridge deck concrete is limited to a water-cement ratio of 0.40, workability may be a problem with smaller aggregate mixes. Providing sufficient workability for placement while maintaining a 0.40 water-cement ratio will require water-reducing admixtures possibly including high range water-reducers.

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