Determining the Rheological Properties of Fresh Concrete using Concrete Shear Box

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Abstract: ***A test method which is accurate, viable and is based on the fundamental scientific description and at the same time the results are independent of the test device can go a long way in better understanding of the workability of fresh concrete. The principal objective of this research study is to assess the feasibility of concrete shear box to measure the rheological properties of fresh Portland cement concrete using Bingham model. Study assesses the repeatability and reproducibility of the results. The repeatability values of relative yield stress and relative plastic viscosity are 97.63% and 91.49% and reproducibility values are 91.68% and 95.51% respectively and the results reinforce the effectiveness of using concrete shear box.***

Keywords: Rheology, Concrete Shear Box, Relative Yield stress, Relative Plastic Viscosity, Repeatability, Reproducibility

I. INTRODUCTION

A test method which is accurate, viable and is based on the fundamental scientific description and at the same time the results are independent of the test device can go a long way in better understanding of the workability of fresh concrete [1]. This can result in improved hardened concrete quality, reduced cost and most importantly pave the way to the use of new and unused marginal materials [2]. The application of the concept of Rheology - a scientific study based on the flow and deformation of matter - to the workability of concrete has made progress in concrete industry [3]. The Rheology of concrete has emerged as a viable technique for characterizing the workability of fresh concrete to overcome the deficiencies of the empirical tests [4]. It is reemphasized that widely used empirical test, measure only one parameter which is ineffective in fully characterizing the concrete behaviour and rheological parameters can be more effective. Any attempt to study rheological properties of fresh concrete is very much essential and need of the hour to understand the behaviour of fresh concrete. This is especially important while using a new instrument [5].

II. METHODOLOGY

The selection of the constituent materials of concrete such as cement, fine aggregate, coarse aggregate and chemical admixtures was done with extreme care and all the materials were locally available and are procured from the single source and in one go. For characterizing the materials standard IS methods were used.

The mix calculations were carried out based on the absolute volume concept by considering the range of cement as per the requirement of IS code with due importance from the point of view of durability and the range of water is considered from the field practice for normal concrete that is prevalent in the local area. Concrete shear box which is specially designed and fabricated is used for finding the rheological properties namely yield stress and plastic viscosity by using Bingham model is discussed in detail in the subsequent sections [6, 7].

Twelve mixes were designed based on absolute volume concept for different cement contents and water contents. Totally 1296 trials were conducted to determine the rheological properties of different concrete mixes. The cement is varied from a minimum of 300 to maximum of 450 kg/m^3 with an interval of 50 kg/m^3 satisfying the conditions as per the codal provisions IS 456-2000 for minimum and maximum values cement for structural concrete based on durability requirements. The water content is varied from 160 to 190 lt/m^3 with an interval of 15 lt/m^3 keeping in mind the practice in the field for the range and also to get the required workability. In this study specifically use of admixtures is avoided so as to understand the feasibility of using fabricated concrete shear box for determining the rheological properties of basic concrete ingredients in fresh state and to avoid any additive ingredient to minimize the influence of it. The use of admixtures alters the behaviour of fresh concrete and the study is mainly focused on the ingredients of basic concrete in fresh state. The design calculation intends to focus on the influence of the ingredients on the fresh properties rather than on the hardened properties.

In this study, the rheological properties of twelve concrete mixes considered were considered to check for repeatability and reproducibility limits. The variability of the measurement caused by the operator (repeatability) and the measurement system (reproducibility) was accounted in this phase. Repeatability conditions accounts the results obtained by conducting the test on an identical specimen performed by same operator using same equipment in the same laboratory under same controlled conditions. Reproducibility conditions accounts for the result obtained by conducting the test on an identical specimen performed by different operators using different equipment in the different laboratory.

III. EXPERIMENTAL FRAMEWORK

In order to have a better spread of the data repeatability condition was performed by single operator on twelve freshly prepared mixes with each mix subjected to five trials. Reproducibility condition was performed by two operators for the same twelve concrete mixes and was subjected to shear test by each operator separately.

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Totally twenty-four mixes were tested with 540 trials considering the normal stress and the displacement rates so chosen. Fresh concrete was subjected to shear test immediately after mixing taking care to complete the entire experiment within 10 to 20 minutes after mixing.

To determine the repeatability and reproducibility limit the "Analysis of variance" method popularly known as ANOVA method is used. For quantifying the repeatability and reproducibility ANOVA is the most accurate method and it allows determining the variability of the interaction between the appraisers and parts. Analysis of variance method for determining the repeatability and reproducibility limit was followed as per Indian standard code IS 15393 (part-1 to Part-6)-2003 [8, 9, 10, 11, 12, 13] which is identical with International standards ISO 5725 (part-1 to part-6)-1994.

The figure 1 and 2 shows the flow chart of the experimental work carried out in this study.

Fig 1. Flow chart showing the experimental work for repeatability condition

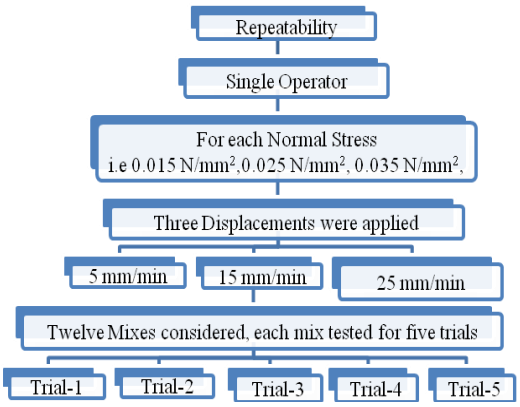


Fig 2. Flow chart showing the experimental work for reproducibility condition

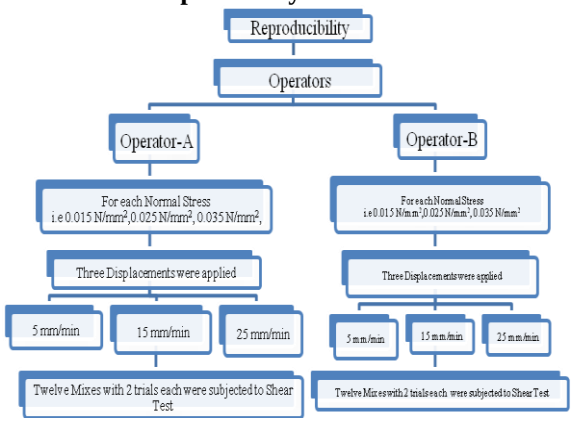


Table I: Mass and volume fractions of concrete mix proportions

Mix	Vp	W/C	Cement (kg/m^3)	Water (lt/m^3)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	V_{ce}	V_{agg}	V_{fa}	V_{ca}
M_1	0.25	0.53	300	160	798	1206	0.095	0.75	0.40	0.60
M_2	0.27	0.46	350		777	1174	0.111	0.73		
M_3	0.29	0.40	400		755	1142	0.127	0.71		
M_4	0.30	0.35	450		745	1126	0.143	0.70		
M_5	0.27	0.58	300	175	777	1174	0.095	0.73		
M_6	0.29	0.50	350		755	1142	0.111	0.71		
M_7	0.30	0.44	400		745	1126	0.127	0.70		
M_8	0.32	0.39	450		724	1093	0.143	0.68		
M_9	0.28	0.63	300	190	766	1158	0.095	0.72		
M_{10}	0.30	0.54	350		745	1126	0.111	0.70		
M_{11}	0.32	0.47	400		724	1093	0.127	0.68		
M_{12}	0.33	0.42	450		713	1077	0.143	0.67		

A. Procedure for determining the rheological properties

The procedure followed to determine the rheological properties is illustrated in this section. Figure 3(a) to (i) shows the relation between shear stress versus shear strain and the graphs show the plots of all the five trials in the same graph. This is for one mix, similar procedure was followed for other mixes. From this relation the peak shear stress for all the trials will be obtained. Likewise, the peak shear stress for three displacement rates and three normal stresses for all the other mixes are obtained. Further peak shear stress values versus normal stress values are plotted and are shown in figure 4(a) to (o) and the shear stress at zero normal stress is obtained. Finally, shear stress at zero normal stress is plotted against displacement rates to get the relative yield stress and relative plastic viscosity. These plots are shown in figure 5. The intercept of the line on the y-axis (shear stress axis) is the yield stress and the slope of this line is the relative plastic viscosity similar to Bingham parameters.

The significance of the test is the low shear rate applied on the specimen during testing which is similar to the condition experienced by the concrete in the field and also the static condition of the test.

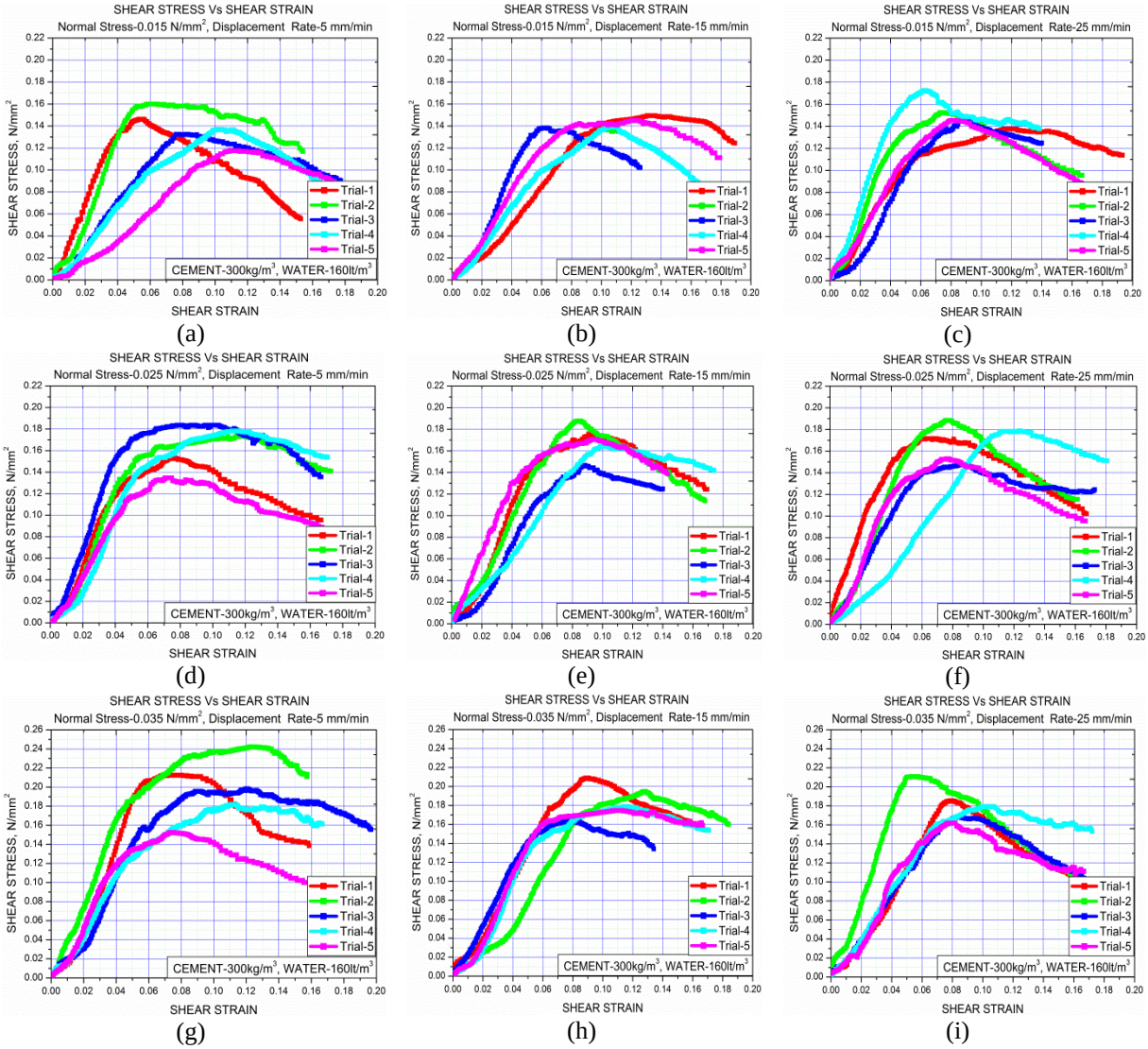
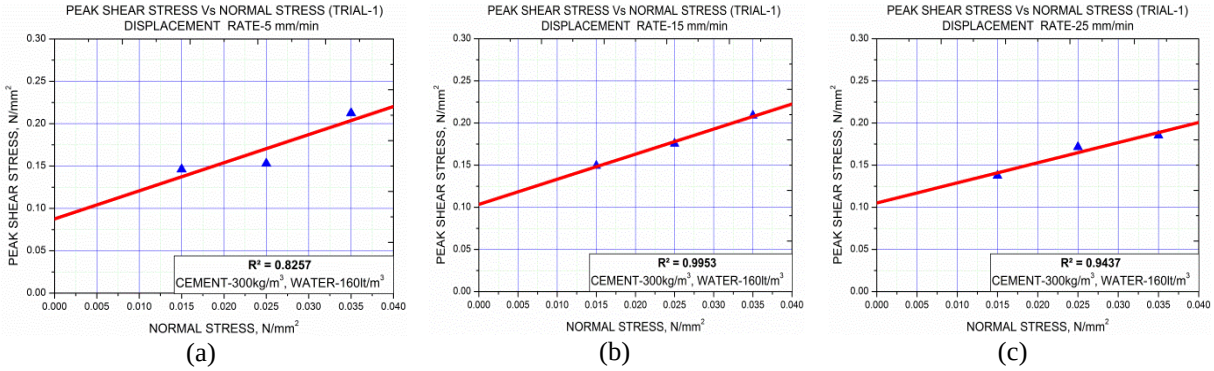
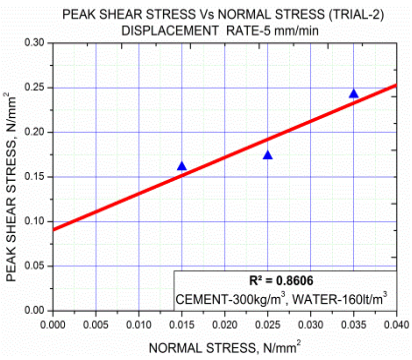


Fig 3 (a)-(i) Relation between shear stress versus shear strain





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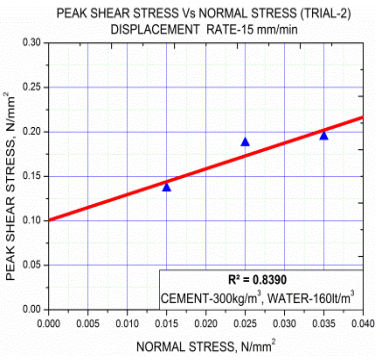

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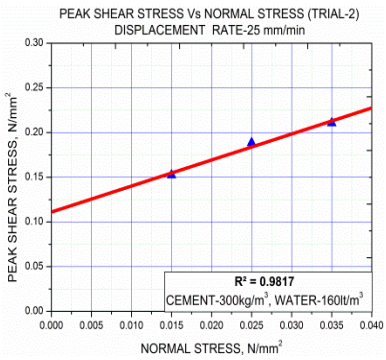

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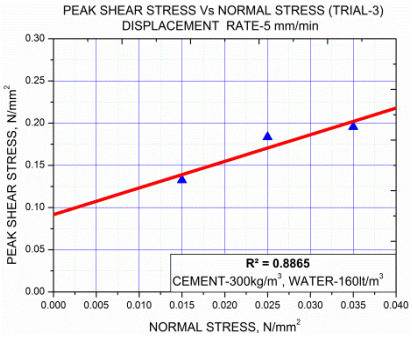

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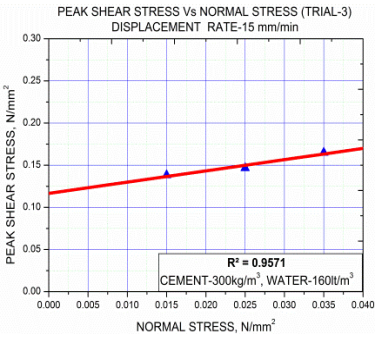

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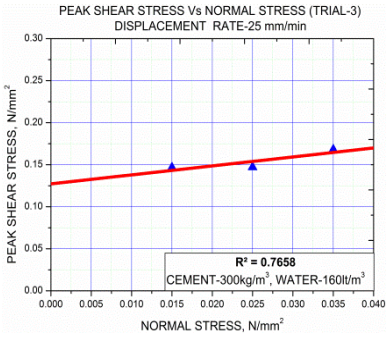

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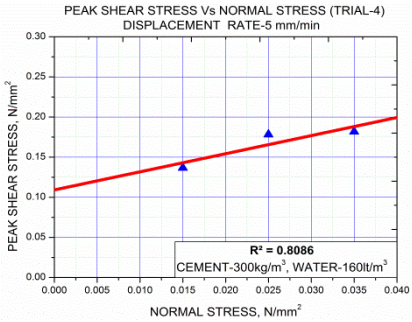

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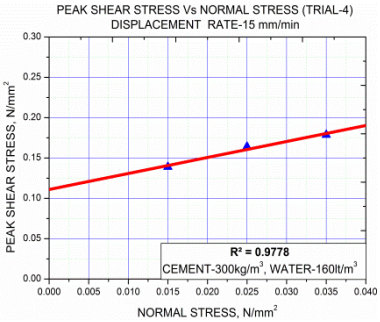

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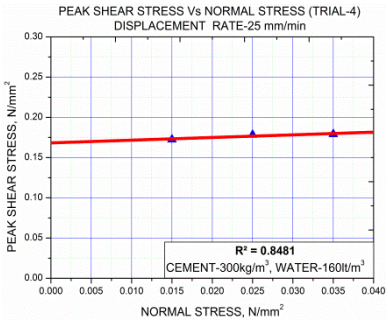

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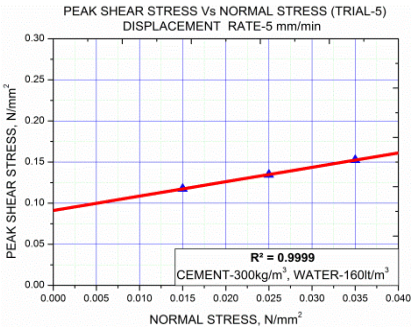

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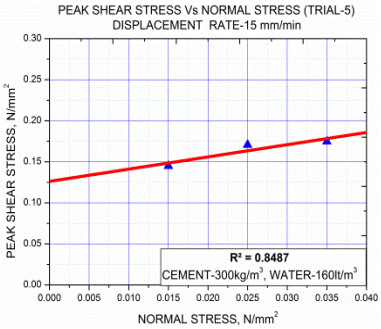

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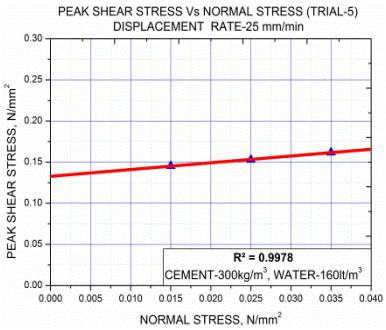

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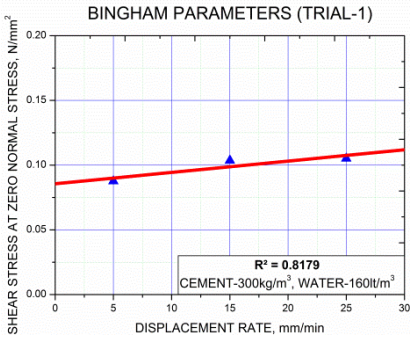
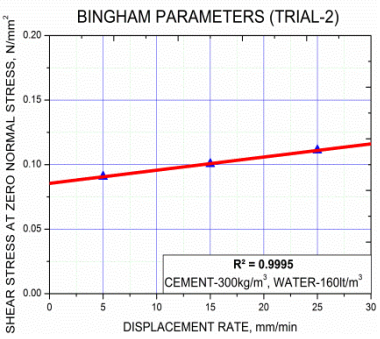
Fig 4 (a)-(o) Relation between peak shear stress versus normal stress



(a)



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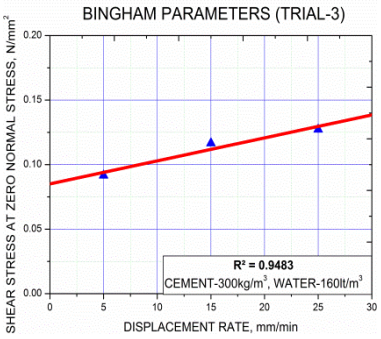

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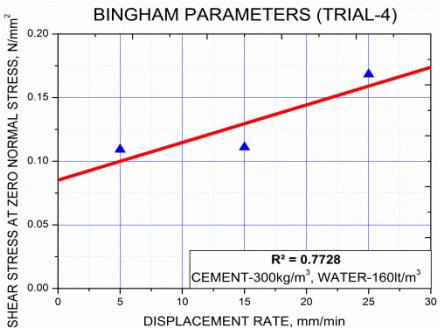

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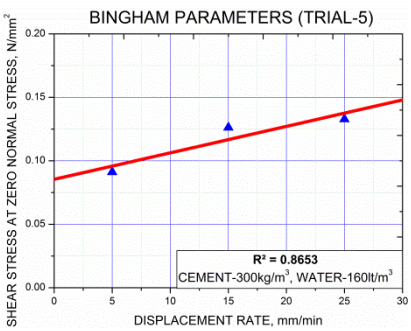

(e)

Fig 5 (a)-(e) Relation between yield stress at zero normal stress versus displacement rate

B Calculation of Bingham parameters for all the mixes

Table II shows the bigham parameters namely the yield stress and plastic viscosity for all the mixes based on individual trials. Totaly five trials were done for assessing the repeatability of the results. Assessment of the repeatability values of relative yield stress and relative plastic viscosity using ANOVA method will be discussed in detail in the section IV. Only the Bingham parameters are tabulated for discussion after obtaining the same following the procedure outlined in the sections III.

Table II: Yield stress and plastic viscosity values of all mixes with five trials

Mix	Vp	W/C	Yield Stress, N/mm^2					Plastic Viscosity, MPa-Sec				
			Trial-1	Trial-2	Trial-3	Trial-4	Trial-5	Trial-1	Trial-2	Trial-3	Trial-4	Trial-5
1	0.25	0.53	85600	85500	85100	85200	85400	12.78	12.86	12.86	12.78	12.60
2	0.27	0.46	78500	78100	78200	78100	78800	18.56	18.91	18.82	18.91	18.30
3	0.29	0.40	76500	76000	77100	76900	76800	22.88	23.31	22.36	22.53	22.62
4	0.30	0.35	64100	64900	64600	64700	63400	30.99	31.17	31.42	31.34	31.60
5	0.27	0.58	78200	78700	78100	78400	78300	18.82	18.39	18.91	18.65	18.73
6	0.29	0.50	75100	75300	75500	75400	75000	21.50	21.32	21.15	21.24	21.58
7	0.30	0.44	70100	70200	70100	70800	70900	25.81	25.73	25.81	25.21	25.12
8	0.32	0.39	53200	53300	52600	53000	53100	40.40	40.32	40.40	40.14	40.06
9	0.28	0.63	76300	76200	76400	76500	76800	20.46	20.55	20.37	20.29	20.03
10	0.30	0.54	72100	72300	72200	72600	72400	24.09	23.91	24.00	23.74	23.83
11	0.32	0.47	63000	63700	63900	63800	63000	31.94	31.34	31.17	31.25	31.94
12	0.33	0.42	49600	49000	49400	49200	49600	43.51	44.03	43.68	43.86	43.51

Influence of volume of paste can be observed from the results. It is again emphasized that at higher volume of paste there will be better lubrication of the aggregate particles thereby, reducing the inter-particle friction and also probably due to better coating of the paste on the aggregates, the yield stress reduces and makes the mix cohesive which is reflected in the plastic viscosity values. A clear trend is noticed in measurement of rheological properties using concrete shear box and it can also be used as an additional tool, in qualifying the fresh properties of concrete in static state.

IV REPEATABILITY CALCULATION FOR YIELD STRESS

To determine the repeatability of yield stress, 12 mixes measured by single operator is considered. The Operator has conducted five trials on each mix. The yield stress values obtained are tabulated in table II.

A. Sum of variation calculations

Variations in the measurements can be by Appraisers, or by Mixes, or by Interaction (Appraiser, mixes) or by gage (Error).

B. Variation by Appraiser

The variation by appraiser can be calculated by,

Sum of square for appraisers, SSA = $\sum_{i=1}^{a} \frac{(x_i^2)}{bn} - \frac{X_n^2}{N}$

Where, a = number of appraisers,
b = number of mixes,
n = number of trials,
N= $(a \times b \times n)$ total number of readings

In our experiment the number of appraisers, a=1, mixes, b=12 and trials, n=5 and total number of readings,

N= $1 \times 12 \times 5 = 60\ readings$

The sum of sixty readings (12 mixes multiplied by 5 trials) for the single appraiser is 4217800. And the sum of all sixty readings is 4217800.

Therefore, the Sum square for appraiser is given by,

$$SSA = \frac{(4217800)^2}{12X5} - \frac{(4217800)^2}{1X12X5} = 0$$

The sum square of variance due to appraisers is zero. Since single appraiser was considered in this study the no variance was observed due to the appraiser.

C. Variation by Mixes

Variance by Mixes can be calculated by,

Sum of square for mixes, SSB= $\sum_{j=1}^{b} \frac{(x_j^2)}{an} - \frac{x^2}{N}$

The sum of five readings for each Mix (1 appraiser multiplied by five trials) is tabulated in the table III along with a square of the sum and the square of the sum divided by five.

Table III: Sum square of mixes computation

Mix	Yield Stress					Appraiser	Sum of 5 trial	Sum Squared	Sum Square/5
	Trial-1	Trial-2	Trial-3	Trial-4	Trial-5				
1	85600	85500	85100	85200	85400	A	426800	1.82158E+11	36431648000
2	78500	78100	78200	78100	78800	A	391700	1.53429E+11	30685778000
3	76500	76000	77100	76900	76800	A	383300	1.46919E+11	29383778000
4	64100	64900	64600	64700	63400	A	321700	1.03491E+11	20698178000
5	78200	78700	78100	78400	78300	A	391700	1.53429E+11	30685778000
6	75100	75300	75500	75400	75000	A	376300	1.41602E+11	28320338000
7	70100	70200	70100	70800	70900	A	353100	1.2468E+11	24935922000
8	53200	53300	52600	53000	53100	A	265200	70331040000	14066208000
9	76300	76200	76400	76500	76800	A	382200	1.46077E+11	29215368000
10	72100	72300	72200	72600	72400	A	361600	1.30755E+11	26150912000
11	63000	63700	63900	63800	63000	A	317400	1.00743E+11	20148552000
12	49600	49000	49400	49200	49600	A	246800	60910240000	12182048000
Total									3.02905E+11

The Sum square for mixes is given by,

SSB = $3.02905X\ 10^{11} - \frac{4217800^2}{12\times5}$

SSB = 6407719333

D. Variation by interaction of appraiser and Mixes

Variation by interaction of appraiser and mixes is given by,

SSAB = $\sum_{i=1}^{a}\sum_{j=1}^{b}\frac{(X_{ij})^2}{n} - \frac{X^2}{N} - SSA - SSB$

The sum of five trials for each combination of the appraiser and mix is tabulated in the table III along with a square of the sum and the square of the sum divided by five.

SSAB = 3.0295 X $10^{11} - \frac{4217800^2}{60} - 0 -$ 6407719333

SSAB =0

Sixty individual readings were squared and summed the total value gives 3.0291 X 10^{11}. The total sum of square is given by,

TSS = $\sum_{i=1}^{a}\sum_{j=1}^{b}\sum_{k=1}^{n}(X_{ijk})^2 - \frac{X^2}{N}$

TSS =3.0291 X $10^{11} - \frac{4217800^2}{60}$ = 6412719333

The sum of square for the gage or error is given by,

SSE = TSS – SSA – SSB – SSAB

= 6412719333 - 0 - 6407719333 – 0 = 5 X 10^6

MSE = $\frac{SSE}{ab\ (n-1)} = \frac{5\ x\ 10^6}{1\ x\ 12\ (5-1)}$ =104166.6667

Repeatability Variance = 5.15$\sqrt{MSE}$= 1662.155

Percentage Variance = $\frac{1662.155}{70296.66}$ =2.36%

Therefore Repeatability of Yield stress = 97.64 %

As it can be seen that the repeatability of yield stress values is 97.64% and the results very clearly indicates the effectiveness of using concrete shear box. Any new instrument needs to be acceptable for its effectiveness and the results concur with this.

Repeatability of the plastic viscosity:

To determine the repeatability of plastic viscosity 12 mixes measured by single operator were considered. The operator has measured each mix in 5 trials. The plastic viscosity values obtained are tabulated in the table IV.

A. Sum of variation calculations

Variations can be by Appraisers, or by mixes, or by Interaction (Appraiser, Mixes) or by gage (Error).

B. Variations by appraiser

The variation by appraiser can be calculated by,

Sum of square for appraisers, SSA = $\sum_{i=1}^{a}\frac{(x_i^2)}{bn} - \frac{X_n^2}{N}$

Where,

a = number of appraisers,

b = number of mixes,

n = number of trials,

N= $(a \times b \times n)$ total number of readings

In our experiment the number of appraisers, a=1, mixes, b=12 and trials, n=5 and total number of readings, N= $1 \times 12 \times 5 = 60\ readings$

The sum of sixty readings (12 parts multiplied by 5 trials) for the single appraiser is 1554.39. And the sum of all sixty readings is 1554.39. Therefore the Sum square for appraiser is given by,

SSA = $\frac{(1554.39)^2}{12X5} - \frac{(1554.39)^2}{1X12X5} = 0$

The sum square of variance due to appraisers is zero. Since single appraiser was considered in this section no variance was caused due to the appraiser.

C. Variation by mixes

Variance by mixes can be calculated by,

Sum of square for mixes, SSB= $\sum_{j=1}^{b} \frac{(x_j^2)}{an} - \frac{x^2}{N}$

The sum of five readings for each mix (1 appraiser multiplied by five trials) is tabulated in the table along with a square of the sum and the square of the sum divided by five.

The Sum square for mixes is calculated by,

SSB = 44894− $\frac{1554.39^2}{12 \times 5}$

SSB = 4625.195

Table IV: Sum square of mixes computation

Mix	Plastic Viscosity					Appraiser	Sum of 5 trial	Sum Squared	Sum Square/5
	Trial-1	Trial-2	Trial-3	Trial-4	Trial-5				
1	12.78	12.86	12.86	12.78	12.60	A	63.88	4080.6544	816
2	18.56	18.91	18.82	18.91	18.30	A	93.50	8742.2500	1748
3	22.88	23.31	22.36	22.53	22.62	A	113.70	12927.6900	2585
4	30.99	31.17	31.42	31.34	31.60	A	156.52	24498.5104	4899
5	18.82	18.39	18.91	18.65	18.73	A	93.50	8742.2500	1748
6	21.50	21.32	21.15	21.24	21.58	A	106.79	11404.1041	2280
7	25.81	25.73	25.81	25.21	25.12	A	127.68	16302.1824	3260
8	40.40	40.32	40.40	40.14	40.06	A	201.32	40529.7424	8105
9	20.46	20.55	20.37	20.29	20.03	A	101.70	10342.8900	2068
10	24.09	23.91	24.00	23.74	23.83	A	119.57	14296.9849	2859
11	31.94	31.34	31.17	31.25	31.94	A	157.64	24850.3696	4970
12	43.51	44.03	43.68	43.86	43.51	A	218.59	47781.5881	9556
								Total	44894

D. Variation by interaction of appraiser and mixes

The variation by interaction of appraiser and mixes is given by,

SSAB = $\sum_{i=1}^{a} \sum_{j=1}^{b} \frac{(X_{ij})^2}{n} - \frac{X^2}{N} - SSA - SSB$

The sum of five trials for each combination of the appraiser and mix is tabulated in the table IV along with a square of the sum and the square of the sum divided by five.

SSAB = 44894 − $\frac{1554.39^2}{60}$ −0 − 4625.195

SSAB = 0

Sixty individual readings were squared and summed the total value gives 44902.80.

The total sum of square is given by,

TSS = $\sum_{i=1}^{a} \sum_{j=1}^{b} \sum_{k=1}^{n} (X_{ijk})^2 - \frac{X^2}{N}$

TSS = 44902.80− $\frac{1554.39^2}{60}$ = 4634.0

The sum of square for the gage or error is given by,

SSE = TSS – SSA – SSB – SSAB

= 4634.0 - 0 – 4625.195 – 0

= 8.80

MSE = $\frac{SSE}{ab\ (n-1)}$

= $\frac{6.556}{1\ x\ 12\ (5-1)}$ =0.1833

Repeatability Variance = 5.15$\sqrt{MSE}$

= 2.2048

Percentage Variance = $\frac{2.2048}{25.90}$ = 8.512%

Therefore, Repeatability of plastic viscosity = 91.49 %

Plastic viscosity is a very important property of the concrete. As can be seen, the repeatability of relative plastic viscosity is 91.49% and the result very clearly indicates the effectiveness of using concrete shear box. Any new instrument needs to be acceptable for its effectiveness and the results concur with this.

V. REPRODUCIBILITY CALCULATION FOR YIELD STRESS

To compute the reproducibility of yield stress, twelve mixes were measured by two operators. Each operator has conducted two trials on each mix. The yield stress values are tabulated in table V.

Table V: Yield stress values of all mixes measured by two operators with two trials

Mixes	Operator-A		Operator-B	
	Trial-1	Trial-2	Trial-1	Trial-2
1	85600	85500	85200	85200
2	78500	78100	78800	78100
3	76500	76000	76300	76900

4	64100	64900	64400	64700
5	78200	78700	78400	78400
6	75100	75300	75400	75400
7	70100	70200	70900	70800
8	53200	53300	55200	53000
9	76300	76200	76200	76500
10	72100	72300	72300	72600
11	63000	63700	63100	63800
12	49600	49000	49100	49200

A. Sum of variation calculations

Variations in the measurements can be by Appraisers, or by mixes, or by Interaction (Appraiser, mixes) or by gage (Error).

B. Variation by Appraiser

The variation by appraiser can be calculated by,

Sum of square for appraisers, SSA = $\sum_{i=1}^{a} \frac{(x_i^2)}{bn} - \frac{X_n^2}{N}$

Where,
a = number of appraisers,
b = number of mixes,
n = number of trials,
N= $(a \times b \times n)$ total number of readings.
In our experiment the number of appraisers, a=2, mixes, b=12 and trials, n=2 and total number of readings, N= $2\times 12 \times 2 = 48$.

The sum of four readings for each mix (2 appraiser multiplied by two trials) is tabulated in table VI along with square of the sum and the square of the sum divided by four.

The sum of twenty four readings (12 mixes multiplied by 2 trials) for appraiser-A is 1685500, the sum of twenty four readings (12 mixes multiplied by 2 trials) for appraiser-B is 1689900. And the sum of all forty eight readings is 3375400. Therefore, the Sum square for appraiser is given by,

SSA = $\frac{(1685500)^2}{12X2} + \frac{(1689900)^2}{12X2} - \frac{(3375400)^2}{2X12X2} =$ 403400

Mean square for sum of square for appraisers, MSA = $\frac{SSA}{a-1} = \frac{403400}{2-1} =$ 403400

C. Variation by mixes

Variance by mixes can be calculated by,

Sum of square for mixes, SSB= $\sum_{j=1}^{b} \frac{(x_j^2)}{an} - \frac{x^2}{N}$

Table VI: Sum square of mixes computation

Mix/ Parts	Yield Stress						Sum of 4 readings	Sum Squared	Sum Square/4
	Operator-A			Operator-B					
	Trial-1	Trial-2	Appraiser	Trial-1	Trial-2	Appraiser			
1	85600	85500	A	85200	85200	B	341500	1.16622E+11	29155562500
2	78500	78100	A	78800	78100	B	313500	98282250000	24570562500
3	76500	76000	A	76300	76900	B	305700	93452490000	23363122500
4	64100	64900	A	64400	64700	B	258100	66615610000	16653902500
5	78200	78700	A	78400	78400	B	313700	98407690000	24601922500
6	75100	75300	A	75400	75400	B	301200	90721440000	22680360000
7	70100	70200	A	70900	70800	B	282000	79524000000	19881000000
8	53200	53300	A	55200	53000	B	214700	46096090000	11524022500
9	76300	76200	A	76200	76500	B	305200	93147040000	23286760000
10	72100	72300	A	72300	72600	B	289300	83694490000	20923622500
11	63000	63700	A	63100	63800	B	253600	64312960000	16078240000
12	49600	49000	A	49100	49200	B	196900	38769610000	9692402500
Total									2.42411E+11

The Sum square for mixes is given by,

SSB = $2.42411 \ x \ 10^{11} - \frac{3375400^2}{2 \ X \ 12 \times 2}$ = 5050059200

Mean square for sum of square for mixes, MSB = $\frac{SSB}{b-1} = \frac{5050059200}{12-1} =$ 459096290.9

D. Variation by interaction of appraiser and mixes

Variation by interaction of appraiser and mixes, is given by,

SSAB = $\sum_{i=1}^{a} \sum_{j=1}^{b} \frac{(X_{ij})^2}{n} - \frac{X^2}{N} - SSA - SSB$

The sum of two trials for each combination of appraiser and mixes is tabulated in table VI along with square of the sum and the square of the sum divided by two.

SSAB = 2.42413 X 10^{11} - 2.373609408 X 10^{11} – 403400 - 5050059200

SSAB = 1596600

Mean square for sum of square for variation for interaction of appraiser and mixes, MSAB

MSAB = $\frac{SSAB}{(a-1)(b-1)}$

MSAB = $\frac{1596600}{(2-1)(12-1)}$ = 145145.4545

Reproducibility variance = 5.15 $\sqrt{\frac{MSA-MSAB}{b\,x\,n}}$ = $\sqrt{\frac{403400-145145.4545}{12\,x\,2}}$ = 5852.160

Percentage Variance = $\frac{5852.160}{70320.8333}$ = 8.322 %

Therefore Reproducibility = 91.6779 %

Reproducibility calculation for Plastic Viscosity

To compute the reproducibility of plastic viscosity, twelve mixes were measured by two operators. Each operator has conducted two trials on each mix. The plastic viscosity values are tabulated in table VII.

A. Sum of variation calculations

Variations in the measurements can be by Appraisers, or by mixes, or by Interaction (Appraiser, mixes) or by gage (Error).

B. Variation by Appraiser

The variation of appraiser can be calculated by,

Sum of square for appraisers, SSA = $\sum_{i=1}^{a}\frac{(x_i^2)}{bn}-\frac{X_n^2}{N}$

Where,

a = number of appraisers,

b = number of mixes,

n = number of trials,

N= $(a \times b \times n)$ total number of readings.

In our experiment the number of appraisers, a=2, mixes, b=12 and trials n=2 and total number of readings,

N= $2\times 12 \times 2 = 48.$

The sum of twenty four readings (12 mixes multiplied by 2 trials) for appraiser-A is 623.58, the sum of twenty four readings (12 mixes multiplied by 2 trials) for appraiser-B is 620.89. And the sum of all forty eight readings is 1244.47. Therefore, the Sum square for appraiser is given by,

SSA = $\frac{(623.58)^2}{12X2}+\frac{(620.89)^2}{12X2}-\frac{(1244.47)^2}{2X12X2}$ = 0.15075

Mean square for sum of square for appraisers, MSA = $\frac{SSA}{a-1}$ = $\frac{0.15075}{2-1}$ = 0.15075

C. Variation of mixes

Variance by mixes can be calculated by,

Sum of square for mixes, SSB= $\sum_{j=1}^{b}\frac{(x_j^2)}{an}-\frac{x^2}{N}$

The sum of four readings for each part (2 appraiser multiplied by two trials) is tabulated in table VII along with square of the sum and the square of the sum divided by four.

Table VII: Sum square of mixes computation

Mix	Plastic Viscosity						Sum of 4 readings	Sum Squared	Sum Square/4
	Operator-A			Operator-B					
	Trial-1	Trial-2	Appraiser	Trial-1	Trial-2	Appraiser			
1	12.78	12.86	A	12.86	12.78	B	51.28	2629.6384	657
2	18.56	18.91	A	18.82	18.91	B	75.20	5655.0400	1413
3	22.88	23.31	A	22.36	22.53	B	91.08	8295.5664	2073
4	30.99	31.17	A	31.42	31.34	B	124.92	15605.0064	3901
5	18.82	18.39	A	18.91	18.65	B	74.77	5590.5529	1397
6	21.50	21.32	A	21.15	21.24	B	85.21	7260.7441	1815
7	25.81	25.73	A	25.81	25.21	B	102.56	10518.5536	2629
8	40.40	40.32	A	40.40	40.14	B	161.26	26004.7876	6501
9	20.46	20.55	A	20.37	20.29	B	81.67	6669.9889	1667
10	24.09	23.91	A	24.00	23.74	B	95.74	9166.1476	2291
11	31.94	31.34	A	31.17	31.25	B	125.70	15800.4900	3950
12	43.51	44.03	A	43.68	43.86	B	175.08	30653.0064	7663
Total									35957

The Sum square for mixes is given by,

SSB = 35957− $\frac{1244.47^2}{2\,X\,12\times 2}$ = 3692.300

Mean square for sum of square for mixes, MSB = $\frac{SSB}{b-1}$ = $\frac{3692.300}{12-1}$ = 335.6636

D. Variation of interaction of appraiser and mixes

The sum of square for variation for interaction of appraiser and mixes, SSAB is given by

SSAB = $\sum_{i=1}^{a}\sum_{j=1}^{b}\frac{(X_{ij})^2}{n}-\frac{X^2}{N}-SSA-SSB$

The sum of two trials for each combination of appraiser and mix is tabulated in table VII along with square of the sum and the square of the sum divided by two.

SSAB = 35951 – 32264.6996 – 0.15075 – 335.6636

SSAB = 1350.4860

Mean square for sum of square for variation for interaction of appraiser and mixes, MSAB.

MSAB = $\frac{SSAB}{(a-1)(b-1)}$

MSAB = $\frac{1350.4860}{(2-1)(12-1)}$ = 122.7714

Reproducibility variance = 5.15 $\sqrt{\frac{MSA-MSAB}{b\ x\ n}}$ = $\sqrt{\frac{122.7714-0.15075}{12\ x\ 2}}$ = 110.64081

Percentage Variance = $\frac{110.64081}{25.9264}$= 4.489 %

Therefore Reproducibility = 95.51 %

Plastic viscosity is a very important property of the concrete. As it can be seen that the reproducibility of relative plastic viscosity is 95.51% and the results very clearly indicates the effectiveness of using concrete shear box. Any new instrument needs to be acceptable for its effectiveness and the results concur with this.

VI. CONCLUSION:

Rheometer is a device to measure the rheological properties of fresh concrete and there are various rheometers available with each rheometer having its own advantages and limitations. There are many challenges like the presence of dead zone, wall effect, slippage problem, gap size based on maximum aggregate size, geometry restrictions, sample volume, sample type (dry or stiff), needs attention to minimize the errors in the results. However, the most important observation is that the concrete is sheared at very high rate in rheometers.

The development of a new concrete shear box to measure the rheological properties of fresh concrete using Bingham model is very significant in that concrete specimen is subjected to a low shear rate during testing and the static condition of the test is similar to that experienced in actual field condition by the concrete.

This study assesses the rheological properties for repeatability and reproducibility of the test results. Single operator performed the tests for repeatability and two operators performed the test separately for reproducibility on twelve mixes subjected to five trials each. Totally 540 trials were performed in this study. For assessment, "Analysis of variance" method, popularly known as ANOVA method was used as per Indian standard code IS 15393 (part-1 to art-6)-2003 which is identical with International standards ISO 5725 (part-1 to part-6)-1994.

The repeatability values of relative yield stress and relative plastic viscosity are 97.63% and 91.49% and reproducibility values are 91.68 % and 95.51% respectively and the results reinforce the effectiveness of using concrete shear box.

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