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**Technical Paper**

# Effect of clay as deleterious material on properties of normal-strength concrete

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**Abstract:** Sustainability concerns prompted use of crushed aggregates in concrete, wherein deleterious materials might get inadvertently included. Some deleterious materials are allowed up to limiting values by most standards, which, however, are silent about the quantification of their effects on properties of concrete – which would be site specific. For an important Indian infrastructure, this study quantifies effects of clay fines as deleterious material in concrete, on workability (slump) and strength (cube compression; split tensile; flexural tensile tests) around the limit (1% of fine aggregates by weight) stipulated by the Indian standard. The novelty of the study is that, contrary to the literature in this domain, the effects are studied without alteration of the mix proportions – a different practical scenario. The limit of clay fines in concrete allowed by Indian standard was found to be adequate considering strength parameters, but for maintaining target workability, the limit would be revised to 0.5% of the fine aggregates. Generally, the variations of concrete properties with the increasing clay fines were: (1) the workability and split tensile strength reduced monotonically, in non-linear fashion; (2) compressive strength (beyond 7 days) and the flexural tensile strength (modulus of rupture) reduced monotonically in linear manner.

**Keywords**: concrete; clay; workability; compressive strength; modulus of rupture; split tensile strength

## 1. Introduction

During last four to five decades, concrete has grown in popularity as a building material particularly due to its flexibility in the geometry, its resistance to the environment and fire as compared to steel, and cost effectiveness. The concrete generally consists of the ingredients: coarse aggregate, fine aggregate, cement and other binding materials, water, and admixtures, as applicable. The design of the concrete mix is performed with the national building codes [1,2] in order to achieve the desired characteristic strength. The mix design, being conducted in the laboratory, happens under strict quality control. However, the actual concrete being mixed either at site (more uncertainty) or at the batching plant (less uncertainty and better control than site mix), there always exist the possibilities of deleterious materials being inadvertently mixed in concrete. In fact, Indian and International codes [3,4] permit certain limiting amount of deleterious material being present in concrete, and still it can be acceptable. However, the standards are silent on the effects of the deleterious material, if present, on the properties of green or hardened concrete.

The deleterious material is defined in literature as materials which might affect the concrete in the following ways:

1) Materials which might interfere with the process of hydration of cement [5];

2) Coatings which would prevent development of good bond between aggregate and cement paste [5];

3) Weak or unsound materials which would affect the strength of concrete [5].

The classification of deleterious materials was conducted as early as 1950-s [6]. Broadly classified, the deleterious materials would fall under the following categories:

1) Organic impurities: they interfere with the hydration process of cement. They are generally present in the form of humus or organic loam and mostly found in the fine aggregates [5,6].

2) Clay and other fine materials: Clay is usually present in the form of coating on the aggregates and interferes with bond between aggregates and cement matrix. Silt and other fine materials might be present as coatings, when the bond is affected; or as loose

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particles which are not bonded and reduces the strength and durability of concrete [5,6].

3) Salt contamination: mostly occurs when the fine aggregate (sand) originates from sea and is a major durability concern as it could effect chloride induced corrosion of reinforcement [5,6].

4) Unsound particles: these are particles which might lose their integrity after casting of concrete or might undergo disruptive expansion in contact with water or in case of freezing. Clay lumps, if present in concrete, would be considered as the unsound particles [5,6].

In developing countries, the issue of utilization of locally available aggregates for concrete has been examined [7]. The effect of presence of clay in concrete has been investigated by many researchers across the world [8-21], and techniques have been proposed to evaluate the possible harmful influences of the clay in concrete [21].

There has been a growing concern of the ecological and environmental impacts of the large scale quarrying or dredging conducted for the supply of aggregate as raw materials for concrete. These include the destruction of habitat, disruption of food chains, disturbance to the local ecology, instability of the courses of rivers, increased erosion, scour, or depositions on the banks of rivers or the coasts due to sand dredging, and changes in the river regimes or coastal hydrodynamics [22]. Therefore, researchers all over the world are exploring alternate sources of aggregate such as recycled concrete, building materials, glass, tyres or ceramic tiles [22-25]. The disposal of the excavated materials from major construction projects pose another concern which often becomes extremely expensive because of the large lead distances involved between the construction sites and the disposal site. As a practical solution to either of the aforementioned problems, in many projects, the practice of using crushed aggregates from the excavated rock from the same site is presently getting preference from sustainability considerations [26-28].

Till recently, use of crushed fine aggregates was less popular in Indian construction projects, particularly due to the lack of experience and data. But experience from the earlier works and stipulations of the national codes [3] have fostered use of up to 100% crushed coarse and fine aggregate manufactured from the locally excavated rock, provided they met the quality standards [3]. In a major infrastructure project in India, the same scheme was adopted and the excavated rock (Fig. 1a) from the site was crushed in the local crusher plants (Fig. 1b) for subsequent use as aggregates, both coarse and fine, in normal-strength concrete. The geology of the site showed that the major rock type was sandstone with clay matrix. This could lead to contamination of crushed aggregates with clay. Clay being an unsound particle would act like weak intrusion in concrete mix. The standard practice of preparation of aggregates includes washing procedure, precisely for removal of such impurities. However, the possibility of clay in the concrete made with the crushed aggregates from the excavated rock could not be ruled out. It has been mentioned earlier that the national code allows a certain amount of clay in the concrete (1% for India [3]), but does not specify the effect on the workability or strength of concrete. There are various limits of clay in concrete based on its mineral composition available in literature [20]. This is understandable as the deleterious materials, in this case – clay, would vary in properties from site to site and consequently, the effect on concrete properties could also be different. The deleterious materials being site specific, the study on the effect of the same on concrete would also be site specific. As the project was of national importance, the possible effects of inadvertent inclusion of clay on the properties of fresh and hardened concrete were deemed necessary to be critically examined.

(a) (b)

Fig 1: (a) excavated rock at site; (b) crusher plant at site

Schuster [8] presented a detailed review of the studies pertaining to the effects of various deleterious materials present in concrete aggregates on the properties of concrete. The effect of very fine aggregate was reported as increase in the 91-day strength, at constant workability [9]. Though some researchers [29] indicated that very large amount of fines could be incorporated into concrete without much detrimental effect on its properties. Abou-Zeid and Fakhry [10] reported that addition of clay fines to concrete in even small amount reduced the workability to a significant extent, though small proportions of clay increased the compressive strength by a certain extent. Gullerd [11] examined the effects of various aggregate coatings on the performance of Portland cement concrete, including durability (drying shrinkage, freeze-thaw, chloride vulnerability) and strength (compressive) and concluded that the clay coatings were more detrimental compared to the dust or carbonates. Munoz et al. [12] conducted detailed experimentation on the effect of clay coatings on aggregates and reported that fraction of clay getting detached and entering water phase would depend on the original clay content as well as the properties of clay, which could vary from site to site. The clay in cement paste affected the rate of hydration, and this effect would also be dependent on the nature of clay, they indicated. Katz and Baum [13] explored the higher levels of fines on the strength properties of concrete with detailed experimental program, but using concrete of constant workability. They concluded that as long as workability was controlled to the target values by addition of suitable admixtures, the strength of concrete increased up to 30% with increases in volume change of fresh and hardened concrete – with addition of small amounts of fines.

Munoz et al. [14] examined the effects of various aggregate coatings and films on the concrete performance, and concluded that the clay coatings were more harmful than other microfine mineralogy such as dust or carbonates, the observations being similar to earlier literature [11]. Cramer [30] indicated that the stipulations of the codes might not be adequate in assuring the desired properties of concrete when microfines were concerned, due to their typical mineralogical composition. They investigated the effect of microfines on strength and workability of concrete, and concluded that dolomitic microfines did not affect workability much, but clay microfines definitely affected the workability adversely with a little improvement in strength properties. Abib et al. [15] explored the properties of self-compacting concrete with fine clay from waste crushed brick, and concluded that the strength improved with up to 5% of the fine clay addition.

The earlier studies examined the strength properties of concrete at constant workability – a condition which might not actually exist at a construction site. Hence, in this study, the concrete mix is kept unaltered, and the effect of clay on both workability and the strength of concrete are studied for different proportions of clay in concrete. To the knowledge of the authors, this approach has not been earlier reported in literature. The initial results of the experiments were presented by the authors in a conference earlier [16] and the analysis of the complete set of results is presented in this article.

This article presents the investigation conducted with slump test for the workability of fresh concrete and a series of cube and cylinder tests for the strength properties of hardened concrete at different ages from 7 days to 91 days. The effect of clay as deleterious material in concrete was investigated around the acceptable limit stipulated by the Indian code [3]. The results of this study would help to reaffirm the limit stipulated in the code as acceptable for the site, or would help to fix site specific limit on the clay in aggregates for attaining the desired strength and workability of the resulting concrete.

## 2. Methodology

### 2.1 Standard mix design

The grade of concrete for the facility was M25, that is, the 95 percent confidence value of 28-day cube compressive strength was 25 MPa. The target slump value was 120 mm, measured according to the Indian standard [31]. The design of the concrete mix was carried out at the site according to the Indian standard [2], and the final proportions for the M25 mix is reproduced in Table 1 for ready reference. The target strength of the mix thus prepared would be 31.6 MPa.

Table 1 Standard design mix (M25)

| Grade of concrete | W/C ratio | Quantities of materials per cubic meter of concrete | | | | | | Slump (mm) |
|---|---|---|---|---|---|---|---|---|
| | | Cement (kg) | Water (L) | Plasticizer (kg) | Sand (kg) | Coarse aggregate (kg) | | |
| | | | | | | 20 mm | 10 mm | |
| M25 | 0.48 | 334 | 160 | 2 | 806 | 624 | 416 | 120 |

The crushed aggregates used in the mix design, namely, 20 mm, 10 mm, and crushed sand are depicted in Fig. 2(a), Fig 2(b) and Fig. 2(c) respectively.

### 2.2 Properties of deleterious material: clay

The origin of the clay at the site can be traced back to the Vindhyan range of sedimentary layer of reddish black soil [32]. The clay fines have a liquid limit of 42% and plasticity index of 27%, which classifies the fines as clay of medium to high expansion/compression properties, according to Indian standard [33]. The clay fines have a free swell index of 53% lying in the range of very high degree of expansiveness. Particularly, this property might cause porosity in concrete and this might eventually lead to strength and durability issues [11,12,14,30].

### 2.3 Design of experiment: concrete mix with clay

The IS code [3] stipulation is 1% as a maximum for clay to be present in concrete, as a percentage of the crushed fine aggregate by weight. The standard mix (SM) contains no clay, and two mixes are taken between standard mix (SM) and the IS limit. Two other mixes are taken higher than the IS code stipulation, namely, 1.5 times and 2 times the limiting value. All the details of the mixes are reproduced in the Table 2. The workability (slump) was tested for all the mixes before the casting of the cubes and cylinders. The strength tests were conducted at different ages of concrete from 7 days to 91 days and the specific details are listed in Table 3. The cube strength was tested at 7 days, 14 days, 28 days, 63 days and 91 days whereas the cylinder and flexural tests were conducted at 28 days only.

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Fig 2: Aggregates (a) 20 mm; (b) 10 mm; (c) crushed sand; (d) deleterious material: prepared clay before being pulverized

## 2.4 Standard procedure for mixing, casting and curing of concrete specimens

The experiments are targeted towards capturing the effects of deleterious materials which comes to around a thousandth by weight. Hence, it was essential to adopt a carefully formulated Standard Procedure for conducting the experiments, which is briefly discussed in the following sub-sections. These are conforming to the stipulations laid down by the Indian standards [1,34,35].

### 2.4.1 Preparation of materials

All materials are brought to room temperature, that is, within 27ºC ± 3º C, before commencing with the mixing. The cement samples, on arrival at the laboratory, were thoroughly mixed dry by hand so as to ensure the greatest possible blending and uniformity in the material. The cement was stored in a dry place, in air-tight metal containers. Aggregates for each batch of concrete were air dried before using in mix. Water was potable water and was at room temperature. The preparation of the clay, to be added as deleterious material deserves particular mention. The soil was sieved through 75 micron sieve in wet condition (slurry) to collect the clay fines in the pan. This clay slurry is oven-dried and then pulverized to obtain the clay for mixing with concrete during the preparation of various concrete mixes.

### 2.4.2 Proportioning of materials

The proportioning of the materials was done by weight, per cubic meter of concrete according to the mix design listed in the Table 2 for the particular mix. Weigh batching was used for proportioning. The weighing of the cement and each size of aggregate is done to an accuracy of 0.1 percent of the total weight of each batch.

### 2.4.3 Mixing

A small mixing machine was used for mixing of materials. Hand loading was adopted for loading the materials on the mixer. The mixing drum was loaded with about one-half of the coarse aggregates, followed by the fine aggregates, the deleterious material: clay, the cement and finally with the remaining coarse aggregate on top, in that order. The water, in which the admixture was already mixed, was added to the mixing drum just before starting the mixing machinery. The period of mixing was kept not less than 2 minutes and was continued till the resulting concrete was uniform in appearance.

### 2.4.4 Casting of cubes, beams and cylindrical specimens

The size of the cube test specimens was 150 mm × 150 mm × 150 mm, confirming to Indian standard [36]. The average strength of three cubes was reported as the compressive strength at a particular age for the mix, except for 28 days' strength – whence the number of cubes was 13. For the six different mixes (CM, and C1 to C5) and five different ages (7, 14, 28, 63 and 91 days) for test of compressive strength, the total number of cube specimens tested was 150 (Table 3). The cylindrical moulds were of 150 mm diameter and 300 mm length, and they conformed to [36]. The beam moulds were of 150 mm square cross-section and 700 mm length, confirming to [36]. The total number of cylinder specimens as

Table 2 Mix design with clay as deleterious material

| Mix designation | Percentage of clay with respect to sand | Quantities of materials per cubic meter of concrete | | | | | | | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| | | Cement (kg) | Water (L) | Plasticizers. (kg) | Sand (kg) | Deleterious material (kg) | Coarse aggregate (kg) | | |
| | | | | | | | 20mm | 10mm | |
| CM | Nil | 334 | 160 | 2 | 806 | Nil. | 624 | 416 | Control Mix |
| C1 | 0.25 | 334 | 160 | 2 | 804 | 2 | 624 | 416 | - |
| C2 | 0.50 | 334 | 160 | 2 | 802 | 4 | 624 | 416 | - |
| C3 | 1.00 | 334 | 160 | 2 | 798 | 8 | 624 | 416 | IS Code Limit |
| C4 | 1.50 | 334 | 160 | 2 | 794 | 12 | 624 | 416 | - |
| C5 | 2.00 | 334 | 160 | 2 | 790 | 16 | 624 | 416 | - |

well as the total number of beam specimens was 18 (Table 3). All the joints between the various sections of moulds were thinly coated with mould oil in order to ensure that no water escapes during the casting procedure as well as to prevent adhesion of the concrete to the moulds.

### 2.4.5 Compaction

The concrete was filled into the mould in layers approximately 5 cm deep. In placing each scoopful of concrete, the scoop is moved around the top edge of the mould. A total of 35 strokes were given with tamping rod for each layer thus laid. The strokes were given in a manner such that the tamping rod penetrated all the underlying layers. The sides of mould were also tapped to close the voids, which might have been left by tamping rod. Thus, dense compact concrete samples were casted for later testing.

### 2.4.6 Specimen identification

After the initial setting, all the specimens (cubes, cylinders and beams) were labelled with permanent marker with mix designation as show in Table 3 along with the date of casting.

### 2.4.7 Curing

The test specimens, in their respective moulds, were stored in a place free from vibration and away from direct sunlight for 24 ± 1/2 hours from the time of mixing. After this period, the specimens were demoulded, marked and submerged in clean, fresh water for the purpose of curing. The water in which the specimens were submerged was periodically renewed, every seven days.

### 2.5 Standard procedure for tests on concrete specimens

The samples after casting are shown in Fig. 3(a) for cube, Fig. 3(b) for cylinder, and Fig. 3(c) for beam. At the designated date of testing, the samples were taken out of the curing pond and tested according to the standard procedures, discussed in subsequent sub-sections.

### 2.5.1 Slump test for workability

Slump cone method of testing was used for evaluation of workability according to the Indian national standard [31]. The internal surface of the mould was cleaned and made free from superfluous moisture and any set concrete before commencing the test. The mould was placed on a smooth, horizontal, rigid and non-absorbent surface, in the form of a carefully levelled metal plate. The mould was firmly held in place while it was filled. The mould was filled in four layers, each approximately one-quarter of the height of the mould. Each layer was compacted with 25 strokes of the rounded end of the tamping rod, distributed in a uniform manner over the cross-section of the mould, which for the second and subsequent layers penetrated into the underlying layer/s. The bottom layer was tamped throughout its depth. After completely filling the mould, the concrete was struck off level at the top with a trowel, so that the mould is exact1y filled. Any mortar which might have leaked out between the mould and the base plate was cleaned away. Then, the mould was removed from the concrete by raising it slowly and carefully in a vertical direction. This allowed the concrete to subside and the slump was measured immediately thereafter by determining the difference between the height of the mould and that of the highest point of the particular specimen. The slump measured was recorded in terms of millimetres of subsidence of the specimen during the test.

Table 0 Test matrix

| Mix Designation | Number of cubes casted for compressive strength test | | | | | Nos. of cylinders casted for split tensile test | Nos. of beams casted for flexural strength test |
|---|---|---|---|---|---|---|---|
| | 7 days | 14 days | 28 days | 63 days | 91 days | 28 days | 28 days |
| CM | 3 | 3 | 13 | 3 | 3 | 3 | 3 |
| C1 | 3 | 3 | 13 | 3 | 3 | 3 | 3 |
| C2 | 3 | 3 | 13 | 3 | 3 | 3 | 3 |
| C3 | 3 | 3 | 13 | 3 | 3 | 3 | 3 |
| C4 | 3 | 3 | 13 | 3 | 3 | 3 | 3 |
| C5 | 3 | 3 | 13 | 3 | 3 | 3 | 3 |

**2.5.2 Cube test of compressive strength**

Specimens were tested immediately on removal from the water and while they were still in the wet condition [34]. The bearing surfaces of the testing machine was wiped clean and any loose sand or other material were removed from the surfaces of the specimen which would be in contact with the compression plates. The specimen was placed in the machine such that the load would be applied to opposite sides of the cubes as cast, that is, not to the top or bottom. The axis of the specimen was carefully aligned with the centre of thrust of the seating plates. The load was applied without shock and increased continuously at a rate of approximately 140 kg/cm$^2$/min until the resistance of the specimen to the increasing load breaks down and no greater load can be sustained [34]. The maximum load applied to the specimen was then recorded. The measured compressive strength of the specimen was calculated by dividing the maximum load applied to the specimen during the test by the cross-sectional area, calculated from the mean dimensions of the section. In general, Indian standard stipulates that an average of three specimen values should be taken as the representative of the sample, provided the individual variation is not more than ± 15 percent of the average [1]. For 28 days' strength, 13 cubes were tested and the mean of the 13 was taken as the representative compressive strength at 28 days. For all other ages, the average of three samples was adopted as the representative compressive strength.

**2.5.3 Split tensile test**

The split tensile strength test on cylindrical specimens was performed according to the guidelines of Indian national standard [35]. The test specimen was tested in wet condition soon after its removal from the curing tank. The surface in contact with the loading plate was made smooth and free from protruded aggregates or any kind of undulations. The centre line was marked across length of the cylindrical specimen on the opposite sides and the dimensions of the specimen were measured, to the nearest 0.2 mm. The weight of the specimen was measured and recorded. The specimen was placed in the loading machine between the edges of two angles ISA 65x65x6. The specimens were so placed that the edge of the angles coincides with the centre line made on the opposite faces of the cylindrical specimen. The jig was then placed in the machine so that the specimen was located centrally. Care was taken so that the loading through the packing strip was truly axial. The load was applied without shock and increased continuously at a nominal rate within the range 1.2 N/mm$^2$/min to 2.4 N/mm$^2$/min [35]. The maximum load at which the specimen failed was recorded and the split tensile strength $f_{st}$, of the specimen was calculated to the nearest 0.05 MPa using Eq. (1) [35]:

$$f_{st} = \frac{2P}{\pi l d} \tag{1}$$

where,
$f_{st}$ = Split tensile strength of cylindrical specimen (MPa)
$P$ = maximum load applied to the specimen (N),
$l$ = Length of the specimen (mm).
$d$ = Cross sectional dimension of the specimen (mm).

**2.5.4 Flexural test**

The flexural strength test on beam specimens was performed along the guidelines of Indian national standard [35]. As for the earlier samples, the beam specimen was tested in wet condition, soon after its removal from the curing tank and the test was conducted according to the Indian standard [34]. The dimensions and weight of the specimens were recorded before the testing. In this case, surface preparation was not required before placing the concrete beam on the testing machine. The axis of the specimen was carefully aligned with the axis of the loading device. The test setup was done on normal compressive strength testing machine. A channel of depth 150 mm was placed on the bottom loading plate. Over it two angles were placed and welded such that their vertex edge lied towards the top. The distance between the two angles was maintained such that their vertex was 600 mm apart. The beam specimen was placed on these two angles without disturbing the bottom channel and angle setup, with 50 mm overhang on either side of the vertices of the angles. Another channel and angle setup, as described above, was made for the top. In this case, the distance between the vertices of the angles was kept as 200 mm, and these would be the two-point loading locations. When this was placed above the beam centrally, it was thus possible to divide the beam into three equal parts of 200 mm each. After fixing the setup the load application was started, without shock and increasing continuously at a rate such that the extreme fibre stress increased at approximately 7 kg/cm$^2$/min, that is, at a rate of loading of 400 kg/min for the 15·0 cm specimen [34]. The load was increased until the specimen failed, and the maximum load was recorded. The appearance of the fractured faces of concrete and any unusual features in the type of failure was also noted. The flexural strength of the specimen was expressed as the modulus of rupture fcr, which, if ‘a’ equals the distance between the line of fracture and the nearer support, measured on the centreline of the tensile side of the specimen, in cm, shall be calculated to the nearest 0.5 kg/sq.cm using Eq. (2) when ‘a’ is greater than 20.0 cm for 15.0 cm specimen, or Eq. (3) when ‘a’ is less than 20.0 cm but greater than 17.0 cm for 15.0 cm specimen, according to the failure condition:

$$f_{cr} = \frac{pl}{bd^2} \quad (2)$$

$$f_{cr} = \frac{3pa}{bd^2} \quad (3)$$

Where

$f_{cr}$ = flexural modulus of concrete (MPa)
$b$ = measured width of the specimen (mm),
$d$ = measured depth in mm of the specimen at the point of failure (mm),
$l$ = length in mm of the span on which the specimen was supported (mm), and
$p$ = maximum load applied to the specimen (N).

## 3. Results and discussion

In this section, the results of the experiments on workability of green concrete and the strength of the hardened concrete are presented and the salient observations are discussed.

### 3.1 Effect on fresh concrete: workability using slump test

The results of slump value for concrete mix with clay fines as deleterious material are presented in Table 4. The effect observed on the slump values at the explored concentrations (0.25% to 2%) of clay as deleterious material in fine aggregate is reduction ranging from 7% to 22%. The clay present in the concrete mix absorbs the water and reduces the free water thereby reducing the workability. This might also affect the strength properties due to possible lack of water for the purposes of complete hydration of cement. The prevalent practice of evaluation of strength at constant workability (by suitable alteration of water-cement ratio or by addition of suitable admixtures), as reported in literature, would be limited in examining this aspect. This study targets to identify such possible effects on the strength properties of concrete by examining the cases with the design water-cement ratio and the admixture quantity.

The variations in the slump has been presented in pictorial form in Fig. 4, where it can be clearly noted that even at the IS code limit of 1% (C3) the slump is lower than the target slump of 120 mm and hence the IS code [3] limit of clay of 1% is unacceptable for this mix. Thus, for the present case, the limit of clay in concrete is recommended to be revised to 0.5% according to the findings of this study. In literature [30], it had earlier been indicated that the stipulations in codes regarding the microfines such as clay might prove inadequate depending upon their

(a) (b) (c)

Fig 3: Samples (a) cube; (b) cylinder; (c) beam;

Table 4 Results of slump test on green concrete with clay as deleterious material

| Mix designation | Deleterious material (clay) (%) | Slump (mm) | Percent variation | Remarks |
|---|---|---|---|---|
| CM | Nil | 135 | - | Control Mix |
| C1 | 0.25 | 125 | 7 | Acceptable slump |
| C2 | 0.50 | 120 | 11 | Target slump |
| C3 | 1.00 | 110 | 19 | IS code limit - Unacceptable slump |
| C4 | 1.50 | 110 | 19 | Unacceptable slump |
| C5 | 2.00 | 105 | 22 | Unacceptable slump |

mineralogical compositions and this was proved true in this case. Further, that the presence of small amount of clay in concrete might reduce workability to a significant extent, as inferred from this study, was earlier reported in literature [10].

### 3.2 Effect on hardened concrete: compressive strength

The summary of the average compressive strength of cubes for the different ages and the various percentages of clay (deleterious material) are presented in Table 5 (detailed results are provided in the Appendix A). The general trend is observed that for all ages, the higher percentages of deleterious material (clay) result in lower strength. The standard deviation obtained from the 13 samples (as elaborated in Appendix A) for 28 days compressive strength are included in Table 5. The small values of standard deviation (between 1.04 MPa and 1.57 MPa) indicate that the quality control implemented for the experiment was good. However, it is to be noted that the standard deviation estimated from small samples might be prone to errors, and should be used with caution.

The compressive strength as a function of increasing clay percentages in concrete are plotted in Fig. 5a for the various ages. It was observed that at the IS code [3] limit (1%), the compressive strength obtained with the design mix attains the target compressive strength of 31.6 MPa. In fact, the target compressive strength could be achieved with inclusion of up to around 1.6% clay. Hence from compressive strength considerations, the IS code limit may be concluded to be conservative. It may be noted that at the IS code limit of 1% (C3), the compressive strength reduced by around 14%, compared to the control mix (CM), whereas the reduction increased to around 32% for 2% clay (C5). The strength reduction with increasing percentage of clay appears to be linear in this case for all ages, except the 7-day tests.

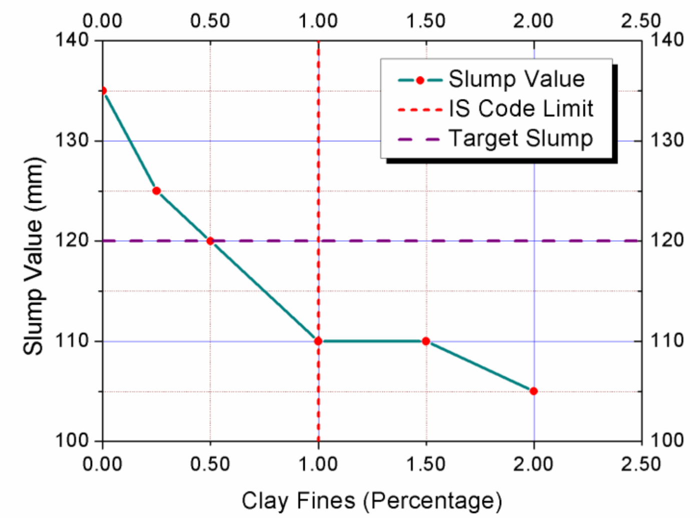


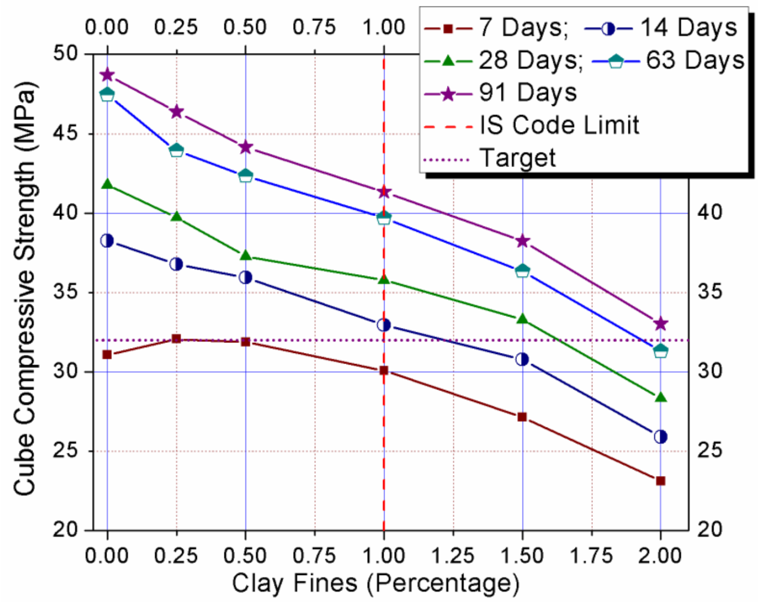

Fig 4: Variation of workability: slump

Table 5 Average compressive strength (MPa) of hardened concrete with clay as deleterious material

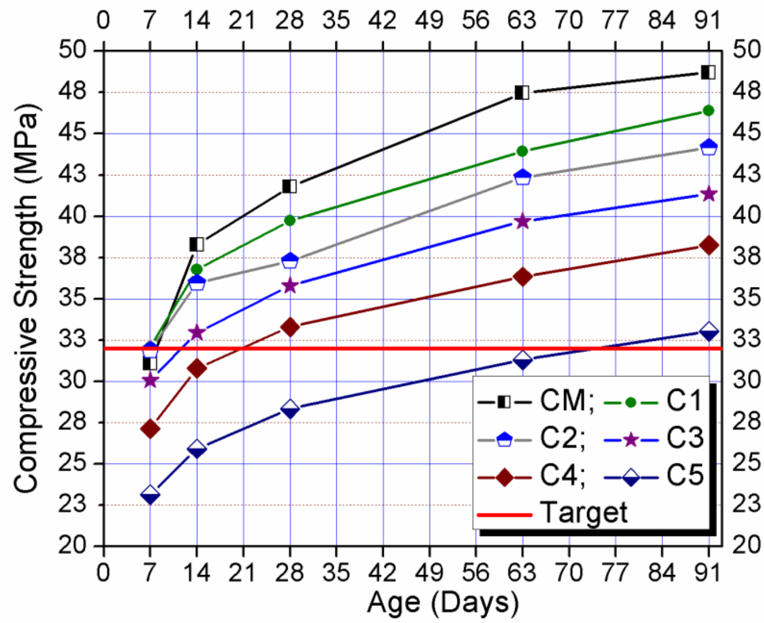
| Mix designation | Age of concrete (days) | | | | | Percent variation of 28 days Strength | Standard deviation of 28-days Strength | Remarks: 28-day strength |
|---|---|---|---|---|---|---|---|---|
| | 7 days | 14 days | 28 days | 63 days | 91 days | | | |
| CM | 31.08 | 38.27 | 41.78 | 47.45 | 48.71 | - | 1.57 | Acceptable |
| C1 | 32.07 | 36.77 | 39.73 | 43.94 | 46.39 | - 5 | 1.25 | Acceptable |
| C2 | 31.88 | 35.96 | 37.28 | 42.34 | 44.15 | - 11 | 1.04 | Acceptable |
| C3 | 30.07 | 32.95 | 35.80 | 39.69 | 41.35 | - 14 | 1.07 | Acceptable |
| C4 | 27.14 | 30.79 | 33.30 | 36.34 | 38.25 | - 20 | 1.26 | Acceptable |
| C5 | 23.13 | 25.91 | 28.34 | 31.30 | 33.04 | - 32 | 1.30 | Unacceptable |

The rate of gain of strength appeared to be affected, particularly in the initial period of hydration. This aspect is examined in the Fig. 5b where the strength development is plotted against the age, for the different mixes. It can be seen in Fig. 5b that the slope of strength gain between age 7 and 14 days is steeper for Mix CM than the mixes with clay as deleterious material, which indicates that the presence of clay reduces the rate of strength gain in concrete. From 7 days to 28 days, the strength gain for Mix CM is 34.4%, for Mix C1 it is 24% and for remaining mixes the gain is around 20%–with reference to the strength at 7 days. This shows that rate of strength gain or the rate hydration is affected due to presence of clay fines. This may be attributed to the high water absorbing property of clay minerals. From 7 days to 28 days, the rate of gain for all mixes appears to be similar and a considerable strength gain takes place.

Increase in average compressive strength continued beyond 28 days, and was observed to be around 15% from 28 to 91 days. Use of fly-ash-based cement, as in this case, improves the concrete strength at later ages due to the pozzolanic reaction [5]. As noted earlier the final compressive strength at any age for concretes with higher percentage of clay fines is lower [17]. This would be possibly




(a)




(b)

Fig 5: Variation of compressive strength: (a) with clay percentage (b) with age because the presence of clay fines in cement paste matrix. Clay fines are soft, have high affinity to water and exhibit high swelling properties [17,18]. This swelled clay particles would dry up with progress of hydration of cement and time, leaving several voids within concrete–which could lead to reduced strength. The presence of clay in the interfacial transition zone may further contribute towards the reduced mechanical properties of concrete [18].

### 3.3 Effect on hardened concrete: tensile strength using split tensile test

The results of the split tensile test of concrete mix with clay fines as deleterious materials are presented in Fig. 6 and the details are tabulated in Table 6. As mentioned earlier, the split tensile strength test was conducted with concrete cylinders at 28 days age of concrete, for all the mixes. It is generally observed that the tensile strength evaluated from split tensile test reduced with the increasing clay percentages in concrete, and the variation was non-linear in the range investigated.

From Table 6, it may be noted that at the IS code limit of 1% (C3), the tensile strength reduced by around 17%, compared to the control mix (CM), whereas the reduction increased to around 30% for 2% clay (C5). The percent reduction in tensile strength at 28 days, evaluated from split tensile test (Table 6, last column), for various percentages of clay as deleterious materials are similar to the variations observed in compressive strength at 28 days (Table 5, last column). The Indian standard [1] stipulates the tensile strength should be determined from the tests conducted on the specimens, and provide a guideline for the flexural tensile strength (= $0.7 \times \sqrt{f_{ck}}$ MPa), but there is no suggested guideline for split tensile strength. Hence, using a conversion factor of 0.8 from cube to cylinder compressive strength [5,34], the correlation between the average cube compressive strength ($f_{cube}$) and the split tensile strength was taken from literature as: $0.2585 \times (f_{cube})^{(2/3)}$ [37] and $0.1711 \times (f_{cube})^{(0.7)}$ [38].

The split tensile strength of concrete as a function of the average cube compressive strength worked out from these relationships are compared to the experimental split tensile strength in Table 7. In

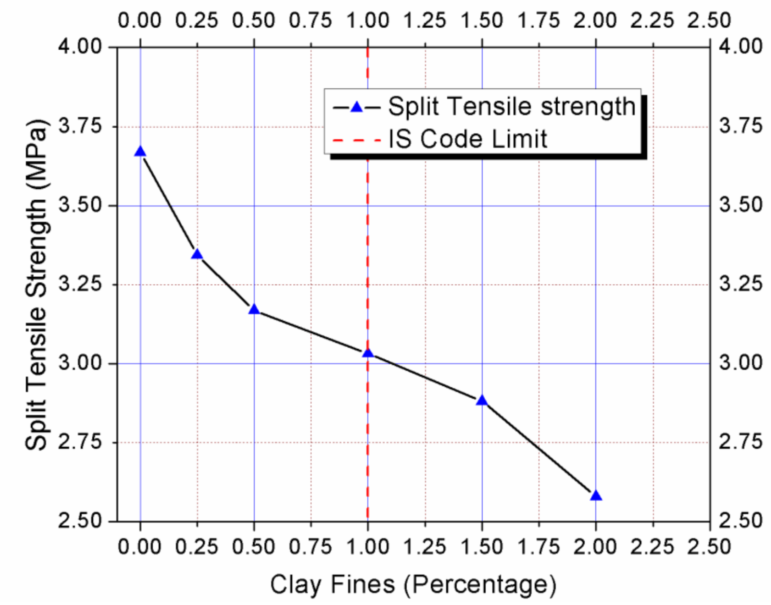



Fig 6: Variation of split tensile strength

Table 6 Split tensile strength of concrete with clay as deleterious materials

| Mix designation | Date of casting | Date of testing | Split tensile strength (MPa) | | | Average split tensile strength (MPa) | Percent variation |
|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | | |
| CM | 04-04-2019 | 02-05-2019 | 3.777 | 3.579 | 3.650 | 3.669 | - |
| C1 | 08-05-2019 | 05-06-2019 | 3.282 | 3.438 | 3.310 | 3.343 | -9 |
| C2 | 09-05-2019 | 06-06-2019 | 3.084 | 3.155 | 3.268 | 3.169 | -14 |
| C3 | 16-05-2019 | 13-06-2019 | 2.943 | 2.985 | 3.169 | 3.032 | -17 |
| C4 | 20-05-2019 | 17-06-2019 | 2.900 | 2.759 | 2.985 | 2.881 | -21 |
| C5 | 20-05-2019 | 17-06-2019 | 2.504 | 2.631 | 2.603 | 2.579 | -30 |

Table 7 Comparison of experimental split tensile strength of concrete with literature

| Mix designation | Average cube compressive strength (MPa) | Split tensile strength from literature (MPa) | | Average split tensile strength (MPa) |
|---|---|---|---|---|
| | | [38] | [37] | |
| CM | 41.78 | 2.33 | 3.11 | 3.669 |
| C1 | 39.73 | 2.25 | 3.01 | 3.343 |
| C2 | 37.28 | 2.15 | 2.89 | 3.169 |
| C3 | 35.8 | 2.09 | 2.81 | 3.032 |
| C4 | 33.3 | 1.99 | 2.68 | 2.881 |
| C5 | 28.34 | 1.78 | 2.40 | 2.579 |

this case, it would appear that the relationships from literature would yield conservative tensile strength value, even up to 2% of deleterious materials (clay) in concrete mix. However, determination of concrete properties for a mix from actual tests should be favored over the use of values stipulated in literature, to get more accurate estimates of the tensile strength.

### 3.4 Effect on hardened concrete: tensile strength using flexural test

The results of the flexural test of concrete beams with clay fines as deleterious materials are presented in Fig. 7 and the details are tabulated in Table 8. As mentioned earlier, the flexural test was conducted with concrete beams at 28 days age of concrete, for all the mixes. It is generally observed that the tensile strength evaluated from flexural tests reduced with the increasing clay percentages in concrete in an almost linear manner.

From Table 8, it may be noted that at the IS code limit of 1% (C3), the tensile strength reduced by around 12%, compared to the control mix (CM), whereas the reduction increased to around 22% for 2% clay (C5). The percent reduction in tensile strength at 28 days, evaluated from flexural test (Table 8, last column), for various percentages of clay as deleterious materials are lower than the variations observed in both compressive strength at 28 days (Table 5, last column) and tensile strength at 28 days from split tensile test (Table 6, last column), though the general reducing trend is common to all. As mentioned earlier, the Indian standard [1] stipulates the tensile strength should be determined from the tests conducted on the specimens, and provides a guideline for the flexural tensile strength (= $0.7 \times \sqrt{fck}$ MPa) from the characteristic strength of concrete (fck). The suggested values in international standards range from $0.623 \times \sqrt{fc}$ MPa to $0.6268 \times \sqrt{fc}$ MPa [39,40], where the average cylinder strength (fc) is used. The comparison is presented with the IS code [1] in this study.

The flexural tensile strength of concrete as a function of the characteristic compressive strength (25 MPa) works out to be 3.5 MPa [1]. In this case, it would appear that the IS guideline [1] would yield conservative flexural tensile strength value for concrete, up to 2% of deleterious material (clay) in concrete mix. However, determination of concrete properties for a mix from actual tests should be favored over the use of values stipulated in literature, to get more accurate estimates of the tensile strength.

## 4. Summary and conclusions

Concrete is extensively used in infrastructure development in modern times. Various replacement options for aggregates for production of sustainable concrete are being attempted and practiced, with a thrust on use of locally available materials for the replacement. The use of 100% crushed fine aggregates in concrete mix has been recently approved by Indian standards, and for wider acceptance, particularly in government sector, evaluation of the various properties of green and hardened concrete using crushed aggregates has become relevant. Particularly, as the crushed aggregates are prone to contain various deleterious materials such as crushed fines (or crusher dust) and clay (from clay matrix in the rock from which the aggregates are produced), evaluation of their effects on properties of concrete needs detail investigation. In fact the codes and standards [3] allow a certain limiting amount of deleterious materials in concrete mix but are silent over the quantification of their effects on the properties of concrete. In literature, various studies are reported wherein the effects of deleterious materials were investigated, but in almost all the cases, the workability was kept constant by addition of extra water or admixtures – which might not be true in actual practice. The present experimental study targeted quantification of the effect of clay fines in concrete mix, at and around the limiting amount of clay fines according to the Indian standard [3,4]. The novelty of the study over the majority reported in literature is that here the original concrete mix proportions were maintained while adding various percentages of clay as deleterious

Table 8 Tensile strength of concrete from flexural test with clay as deleterious materials

| Mix designation | Date of casting | Date of testing | Split tensile strength (MPa) | | | Average split tensile strength (MPa) | Percent variation |
|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | | |
| CM | 04-04-2019 | 02-05-2019 | 4.764 | 5.031 | 4.907 | 4.901 | - |
| C1 | 08-05-2019 | 05-06-2019 | 4.782 | 4.711 | 4.889 | 4.794 | -2 |
| C2 | 09-05-2019 | 06-06-2019 | 4.640 | 4.676 | 4.569 | 4.628 | -6 |
| C3 | 16-05-2019 | 13-06-2019 | 4.409 | 4.320 | 4.249 | 4.326 | -12 |
| C4 | 20-05-2019 | 17-06-2019 | 3.947 | 4.142 | 4.213 | 4.101 | -16 |
| C5 | 20-05-2019 | 17-06-2019 | 3.929 | 3.822 | 3.787 | 3.846 | -22 |

material in concrete mixes. The experiments included the slump test for workability; compressive test, split tensile test and flexural test for strength properties of concrete mix with deleterious materials. The conclusions from the study are as follows:

1) The workability of concrete measured by slump test reduced with increase in percentage of clay from 7% reduction at 0.25% to 22% reduction at 2%. This would be due to the higher water absorption by the clay particles, thereby reducing the free water and resulting in harshness of mix. The observed slump equaled the target slump at 0.5% of clay and was less than target slump for all higher clay percentages in concrete. Hence, the limiting clay percentage is suggested to be fixed at 0.5%, as against the IS code [3] stipulation of 1% of fine aggregates.

2) The 7-day compressive strength increased slightly for clay up to 0.5%, and reduced thereafter. For all other ages, the compressive strength reduced with increased clay percentages monotonically. The reduction varied from 5% for 0.25% to 32% for 2% clay in concrete mix. This could be attributed to the swelling of clay with absorption of water [19] and creation of voids due to drying of the same, thereby reducing strength [17, 19]. Another possible reason could be weakening of the interfacial transition zones due to presence of clay [17]. For 2% clay fines the average 28 day compressive strength was below the target strength and thus would be unacceptable. However, the IS code [3] stipulated value of 1% clay fines would result in acceptable target strength.

3) The split tensile strength reduced with increasing clay percentages monotonically, but in a non-linear fashion. The reduction varied from 9% for 0.25% to 30% for 2% clay in concrete mix. There is no guideline in IS code for the split tensile strength and so the experimental results were compared to values suggested in literature [37,38]. The split tensile strength obtained for the concrete mixes with up to 2% of clay as deleterious material was higher than the values stipulated in literature [37,38].

4) The flexural tensile strength or modulus of rupture reduced with increasing clay percentages monotonically, apparently in a linear fashion. The reduction varied from 2% for 0.25% to 22% for 2% clay in concrete mix. The flexural tensile strength obtained for the concrete mixes with up to 2% of clay as deleterious material was higher than the values stipulated in IS code [1].

The major findings of this study regarding reduction of workability of concrete due to presence of small amounts of clay are similar to [10], and that the limits on microfines such as clay stipulated by the codes might fall short of desired properties and would have to be revised was indicated by [30]. The findings that there was no strength improvement (none except 7 days compressive strength up to around 0.75% of clay), only reduction, was reported in the same study earlier [30]. Increase in strength of concrete due to addition of clay as reported extensively in literature [9,10,13,15,29] was not observed in this case, for any of the strength parameters examined.

Further studies are under progress for evaluation and quantification of the effects of crusher fines for the concrete mix for this site. It is recommended that when crushed aggregates are being used for concrete, the effects of the possible deleterious materials on the properties of green (workability) and hardened (compressive and tensile strength; durability) concrete should be carefully investigated, without addition of extra water or admixtures for maintaining constant workability. As the deleterious materials would be site specific, separate investigation for each source of the aggregates would be desirable. Future studies might be towards investigating the effects of other deleterious materials or even various combinations of the same on the workability, strength and durability properties of concrete.

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