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# INFLUENCE OF SUPERPLASTICISER ON PROPERTIES OF RECYCLED AGGREGATE CONCRETE

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## ABSTRACT

The effect of superplasticizer on various properties of concrete made with 100% recycled coarse aggregate (RCA) was studied in this paper. Two grades: normal strength concrete (M20) and medium strength concrete (M30) were designed with 100% recycled coarse aggregate with and without addition of superplasticizers. Controlled concrete mixes of same grades (M20 & M30) with and without addition of superplasticizers were also prepared with natural aggregate to evaluate the behaviour of recycled aggregate concrete in comparison to normal concrete. Workability, compressive, split tensile and flexural strengths; stress-strain characteristics, rebound number and ultrasonic pulse velocity tests were performed during the investigation. The test results reveal that with the addition of superplasticizer in RAC, it may be possible to achieve the normal and medium strength concrete (M20 and M30) as it was achieved the same with natural aggregate without addition of superplasticizer.

**Keywords:**Recycled aggregate concrete (RAC); ultrasonic pulse velocity (UPV); normal strength concrete; medium strength concrete; tensile strength; superplasticizer.

## 1. INTRODUCTION

In the recent times, the increased population, urbanization, industrial development, etc have made remarkable growth in the infrastructural development in most of the countries, particularly in the field of construction. Therefore, there is a lot of demand for new structures, which requires millions of tons of coarse aggregate, as the coarse aggregate contribute around 60-70% of the total volume of concrete. The natural resources are significantly affected due to extensive usage of aggregate in the construction sector on one side. Also, this will affect the sustainable development of the society. On the other hand,

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most of the countries facing the problem in handing the solid waste, since, there is a huge amount of waste contributed from the construction and demolition of structures. In India, as per the Central Pollution Control Board (CPCB) studies, the solid waste generation is about 48 million tons per annum of which 25% is from the construction industry only. Therefore, the use of recycled coarse aggregate from the construction and demolition waste (C&DW) as an alternative material (aggregates) for making new concrete, acquires the importance to save the natural resources and reduce the need of waste disposal. Indeed, the construction demolition waste deposition has an impact on environment and contributes significantly to the landfill saturation. The maximum possible utilization of the C&DW as an aggregate in concrete is very effective and anticipating technique towards the sustainable development in construction sector.

## 2. LITERATURE REVIEW

In the recent past many researchers have studied the physical and mechanical characteristics of recycled coarse aggregate and the influence of partial replacement of natural coarse aggregate with recycled coarse aggregate on properties of both fresh and hardened concrete [1- 13]. It was reported that the properties of recycled coarse aggregates are relatively weaker than those of the natural coarse aggregates and therefore the properties of recycled aggregate concrete are also relatively lower than those of normal concrete. Nevertheless, 25–30% recycled coarse aggregate has no significant influence on the properties of recycled aggregate concrete (RAC) [9. 13-14]. A few researchers were studied the influence of secondary cementitious materials like fly ash, silica fume, metakaolin, ground granulated blast slag on various properties of recycled aggregate concrete. Kou et al., [15] concluded that the compressive strength of recycled aggregate concrete at different curing periods were lower than that of normal concrete, but with the addition of 10% Silica fume or 15% Metakaolin, this could be indemnified. Nevertheless, the compressive strength was lowered with the use of 30% fly ash or 55% ground granulated blast slag. Elhakam et al., [14] also found that the properties of recycled aggregate concrete can be improved with the addition of 10% silica fume. Kou and Poon [16] reported that due to the pozzolanic reaction between fly ash and $Ca(OH)_2$ in the RAC the mechanical and durability properties of recycled aggregate concrete significantly improved. Similarly, some attempts were made to improve the quality of recycled coarse aggregate by applying various treatment techniques and their influence on mechanical and durability properties of recycled aggregate concrete.

Katz [17] attempted to improve the quality of recycled coarse aggregate by impregnation of recycled coarse aggregate in a silica fume solution and an ultrasonic cleaning of recycled aggregate. The authors found that the compressive strength of RAC was increased by 23% - 33% and 15% respectively at 7 and 28 days by silica fume treatment against an increase of 3% and 7% with ultrasonic cleaning of RCA. This shows that there was a significant improvement in compressive strength at early age when compared to later ages with the silica fume impregnation technique. This was due to filler effect of silica fume which enhances the interface between the new cement matrix and recycled aggregate and hence mechanical properties of recycled aggregate concrete. Tam *et al*. [18] proposed a new method of mixing called two-stage mixing approach (TSMA), in which the whole mixing was separated into two parts and proportionately separates the required water into two parts which are added to the mixes at different timings. This gives the access for gelatin the recycled aggregate with the cement slurry, providing a stronger ITZ by filling up the pores and cracks within the recycled aggregate. The authors found that there was an improvement in compressive strength and other mechanical properties of RAC with this TSMA when compared to normal method of mixing. Tam *et al*. [19] proposed two modified mixing methods with some alterations to the previously proposed TSMA of same authors. The first modified two-stage mixing approach$_{(proportional\text{-}1)}$ ($TSMA_{p1}$), in which the whole mixing was separated into two parts and proportionately splits the required cement and water with the percentage of recycled aggregate in the pre-mix procedure for 60 s and then the rest of the ingredients were added and mixed for 120 s. The second modified two-stage mixing approach $_{(proportional\text{-}2)}$ ($TSMA_{p2}$) follows the similar procedure as $TSMA_{p1}$, in which only the cement was split in two parts without added the water in the first stage. The authors found that the compressive strength of RAC was improved in both the cases of mixing when compared to normal mixing method. Tam *et al*. [20] proposed new treatment methods i.e. pre-soaking of recycled aggregate in three acidic solutions to improve the properties of recycled aggregates and RAC. The authors found that the water absorption of pretreated recycled aggregates was reduced significantly with improved mechanical properties of RAC. At the same time, the alkalinity of RAC and sulphate and chloride contents of recycled aggregate was not affected adversely. Tam and Tam [21] developed diversifying TSMA for the improvement of mechanical properties and microstructure of recycled aggregate concrete with the use of silica fume and cement at pre-mixing stage. The authors found that the addition of silica fume and cement at pre-mixing stage improves the interface layer around the aggregates and thus increase the strength of RAC. Li *et al*. [22] suggested a new technique i.e. recycled aggregate surface coated with pozzolanic powder (fly-ash, silica fume and blast furnace slag)" for improving the quality of recycled aggregate concrete. In this the authors divided the whole mixing into two stages. In the first stage part of the total mixing water was mixed with pozzolanic powder (PP) for one minute to produce slurry and then the RCA was added to the slurry and mixed for another one minute so that the surface of the RCA was coated. At last the rest of the water, fine aggregate and cement were added and mixed for about three minutes. The authors observed that the workability was improved greatly when compared to normal mixing. This was attributed to the thin coating film made from pozzolanic powder which prevents the water absorption of RCA during initial stages of fresh mixes and improves the workability. In addition not much difference observed in slump loss between normal mixing and this mixing. The authors also concluded that the compressive and flexural strengths of RAC were improved with this new technique compared to normal mixing.

A very few attempts have been made on the influence of superplasticisers on mechanical properties of recycled aggregate concrete. Matias et al.[23] studied the influence of different types of superplasticizers on compressive strength and split tensile strength of recycled aggregate concrete. It was reported that the addition of superplasticizer can reduce the loss of compressive strength and split tensile strength in RAC. It was also reported that high performance superplasticizer was more effective in achieveing the required workability and strength when varying the percentage of recycled aggregate. Pereira et al. [24] evaluated the effects of incorporating two types of superplasticizer on the mechanical performance of concrete containing fine recycled aggregate. It was reported that the mechanical performance of concrete made with fine recycled concrete aggregate can be as good as that of normal concrete, if superplasticizers were used to reduce the water–cement ratio of the former concrete.

## 3. SIGNIFICANCE

The properties of RCA, the concrete composition and the type of superplasticiser significantly influence the properties of recycled aggregate concrete. Even though many researchers have studied the influence of the first two parameters, very few attempts have made on the influence of the superplasticizer on RAC properties. Therefore, this paper aims to investigate the influence of 100 percent RCA on various properties of concrete as well as the effect of superplasticiser on the properties of this modified concrete.

## 4. EXPERIMENTAL PROGRAMME

### *4.1 Cement and natural aggregates*

In the present study, Portland Pozzolana Cement (PPC) conforming to the requirements of BIS (IS: 8112-1989) was used. The locally available natural sand and 20 mm maximum size natural coarse aggregate available from the local quarries conforming to the grading requirements of IS: 383 (1970) were used.

### *4.2 Recycled coarse aggregate (RCA)*

The recycled coarse aggregates were obtained from the demolished waste material (concrete debris), which was collected from the dumping yard near Endada, Visakhapatnam. The details of the old concrete debris are unknown. After removal of the impurities like iron, wood etc. manually from the demolished concrete materials, large pieces of size approximately 150 - 200 mm of the demolished waste concrete rubble are transported to the materials testing laboratory of Civil Engineering Department, GITAM University. The large boulders are crushed manually to the maximum size of 20 mm aggregate and sieved manually as per Indian standard Method of sieving. The aggregate of size passing through 20 mm and retained on 4.75 mm sieve size were selected as recycled coarse aggregate (RCA) in the present study.

### *4.3 Superplasticizer*

Conplast BV 40super plasticizer was used in the present study to maintain the uniform workability in all concrete mixes. The superplasticizer is of brownish colour and is available in liquid form. According to the manufacturer data, this superplasticiser confirms the requirements of BIS (IS: 9103 – 1999) (amended in 2003).

### *4.4 Details of concrete mixes*

A normal concrete mix design procedure given in BIS (IS: 10262-2009) was adopted for the mix design of recycled aggregate concrete. The details of concrete mixes for each grade of concrete are presented in Table 1.

Table 1: Details of concrete mixes (quantities are per cubic meter of concrete)

| Concrete Mix designation | Cement (kg) | Fine aggregate (kg) | Coarse aggregate(kg) | Water (liters) | Superplasticizer | Slump (mm) |
|---|---|---|---|---|---|---|
| Without Superplasticizers | | | | | | |
| MN-20 | 383 | 546 | 1187 | 191.61 | Without Superplasticizer | 60 |
| MR-20 | | | 1130 | | | 40 |
| MN-30 | 450 | 514 | 1119 | 191.61 | | 50 |
| MR-30 | | | 1047 | | | 30 |
| With Superplasticizers | | | | | | |
| MNS-20 | 383 | 546 | 1187 | 191.61 | 0.85% by weight of cement | 110 |
| MRS-20 | | | 1130 | | | 90 |
| MNS-30 | 450 | 514 | 1119 | 191.61 | | 100 |
| MRS-30 | | | 1047 | | | 70 |

## 5. RESULTS AND DISCUSSION

*5.1 Physical and mechanical properties of recycled coarse aggregate*

The physical and mechanical properties of fine aggregate, natural and recycled coarse aggregates are determined according to the procedures given in IS 2386 (Part I, III and IV) and are presented in Table 2 along with the limits specified by various authors for RCA.

Table 2: Physical and mechanical properties of fine, natural and recycled coarse aggregates

| Property | Coarse aggregate | | Min/Max. Limits | | |
|---|---|---|---|---|---|
| | | | B.I.S for natural aggregate | WBTC 12/2002 for RCA[25] | SCSS for RCA[26] |
| | NA | RCA | | | |
| Fineness Modulus | 7.16 | 7.06 | | | |
| Bulk density (Compact) in kg/l | 1.41 | 1.2 | | | |
| Bulk density (Loose) in kg/l | 1.20 | 1.04 | | | |
| Specific gravity (SSD) | 2.65 | 2.48 | | | |
| Water absorption (%) | 1.2 | 5.5 | 10 | 10 | 7 |
| Impact value (%) | 26 | 25 | 35 - 45 | | |
| Flakiness Index (%) | 29 | 17 | 25 | 40 | 15 |
| Elongation Index (%) | 27 | 22 | 30 | | |

*5.1.1 Particle size distribution (grading curves)*

The particle size distribution of natural and recycled coarse aggregates is presented in Fig. 1. The minimum and maximum limits specified by BIS (IS: 383-1970) for natural aggregate used in concrete are also presented.

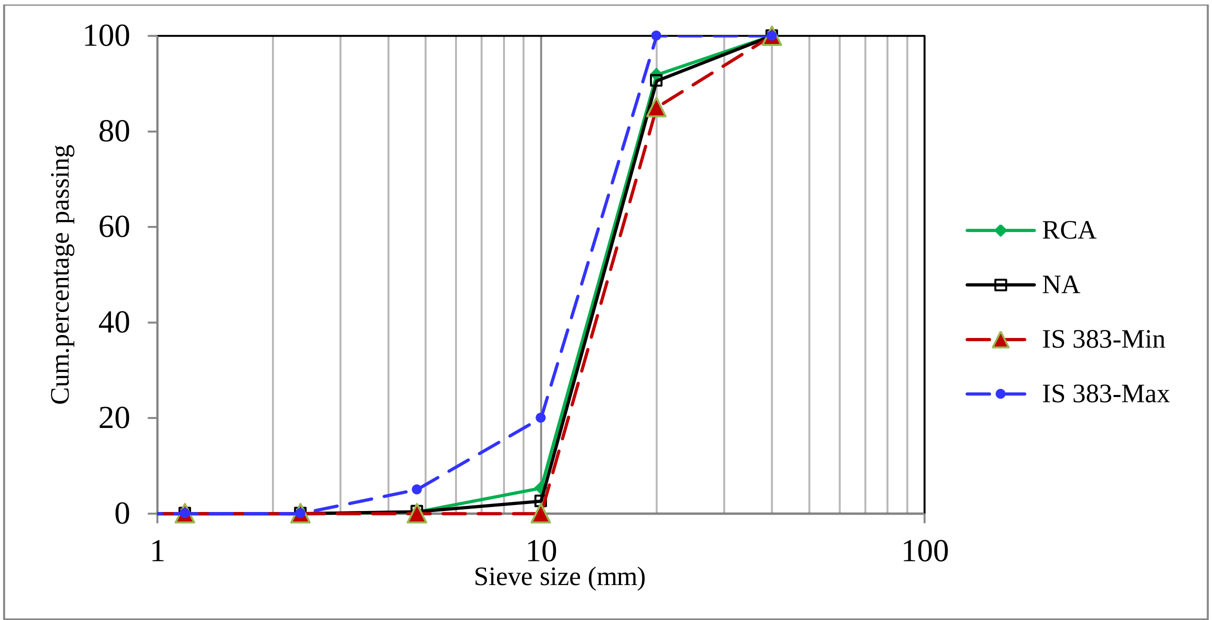


Figure 1. Particle size distribution of both natural and recycled coarse aggregate along with the minimum and maximum limits specified by IS 383

It shows that the grading curves of both natural and recycled aggregates are almost follows the similar trend. Hence, no much difference observed in the fineness modulus of both natural and recycled aggregates. Further, it is observed from the Fig. that the grading limits of both natural and recycled aggregates are well below the limits specified by IS: 383 (1970). Therefore, with the proper method of crushing, the appropriate grading of the recycled aggregates may be produced. After the recycling process the visual observation reveals that due to the attachment of old cement paste to RCA, the surface texture of recycled coarse aggregates are porous and rough. This may demand more water for achieving the requisite workability. Further, this may enhance the interlocking between aggregates and mortar and thereby the bond improves between them.

*5.1.2 Bulk density*

The test results of both compact and loose bulk densities of natural fine and coarse aggregate and recycled coarse aggregate are presented in vide Table 2. It shows that the natural aggregate has higher packing capacity than recycled coarse aggregate. The compact density of natural coarse aggregate is 1410 kg/m$^3$ when compared to 1200 kg/m$^3$ for recycled coarse aggregates that is the compact density of RCA is 1.18 times lower than that of natural coarse aggregate. Similarly, the loose bulk density of RCA is 1.15 times lower than that of natural coarse aggregate. This is due to the adherence of light and porous nature of old cement mortar to the aggregates in RCA.

*5.1.3 Specific gravity*

The specific gravity (SSD) of natural and recycled coarse aggregate are studied in accordance with BIS (IS: 2386-1962 (Part 3)) and the results are shown in vide Table 2. It is observed that the specific gravity of RCA is 2.48 against 2.65 for natural coarse aggregate i.e. the specific gravity of RCA is 7.5% lower when compared to natural coarse aggregate. This attributes the attachment of old porous mortar to the aggregate in RCA. Due to low specific gravity of recycled coarse aggregate, there the amount of recycled coarse aggregate to be used in the recycled aggregate concrete is reduced.

*5.1.4 Water absorption*

The water absorption of both natural and recycled coarse aggregate are measured according to BIS (IS: 2386-1962 (Part 3)) and the results are presented in vide Table 2. The water absorption of natural coarse aggregates is 1.2%. It is important to mention that the water absorption of recycled coarse aggregate is higher than that of natural coarse aggregate. This is expected due to porous and high absorption capacity of old mortar attached to the aggregate in recycled aggregate. The water absorption capacity of RCA is 5.5%, which is approximately 4.6 times higher than that of natural aggregate. However, this is well within the limits specified by BIS for natural aggregate (IS: 383 1970) and for RCA reported in the literature [25-26].

*5.1.5 Flakiness and elongation indices*

The test results of flakiness and elongation indices of natural coarse aggregate and recycled coarse aggregate are presented in vide Table 2. It is observed that the flakiness and elongation indices of natural aggregate are 29% and 27% respectively. On the other hand, the flakiness and elongation indices of RCA are 17% and 22% respectively. These values are well below the requirements of aggregates for normal concrete specified by IS 383 (1970) and WBTC 12/2002 for RCA, whereas, the flakiness index of RCA is slightly higher than the limits specified by SCSS (2007) for RCA [26]. The results reveal that the recycled coarse aggregates manifest better indices when compared to natural aggregates. It is felt that these improvements may be due to the use of manual crushing methodology.

*5.2 Properties of recycled aggregate concrete*

*5.2.1 Workability*

The details of the concrete mixes along with their slump values are presented in vide Table 1. Table reveals that the workability of the recycled aggregate concrete in both normal strength (MR-20) and medium strength (MR-30) is lower than those of concrete with natural aggregate. This may be due fact that the water absorption of the recycled aggregate is 4.6 times higher than that of natural aggregate. After the addition of the superplasticizer the workability of both normal strength (M20) and medium strength (M30) concrete with natural and recycled aggregate is improved when compared to the same without addition of super plasticizer. Nevertheless, the workability of recycled aggregate concrete is lower than the natural aggregate concrete.

(a) Compressive strength development with age

Compressive strength test results of both normal concrete and recycled aggregate concrete with and without addition of superplasticizer are presented in Fig. 2. It reveals that the compressive strength variation (trend) with curing age is almost similar in both normal and recycled aggregate concrete. Further, it is observed that the gain in strength of RAC from 7 days to 28 days of curing period is relatively higher than the concrete with natural aggregate. That is in the last 21 days of 28 days curing period the strength gain in MR-20 and MR-30 is 31% and 18% respectively against 25% and 10% in MN-20 and MN-30 respectively.

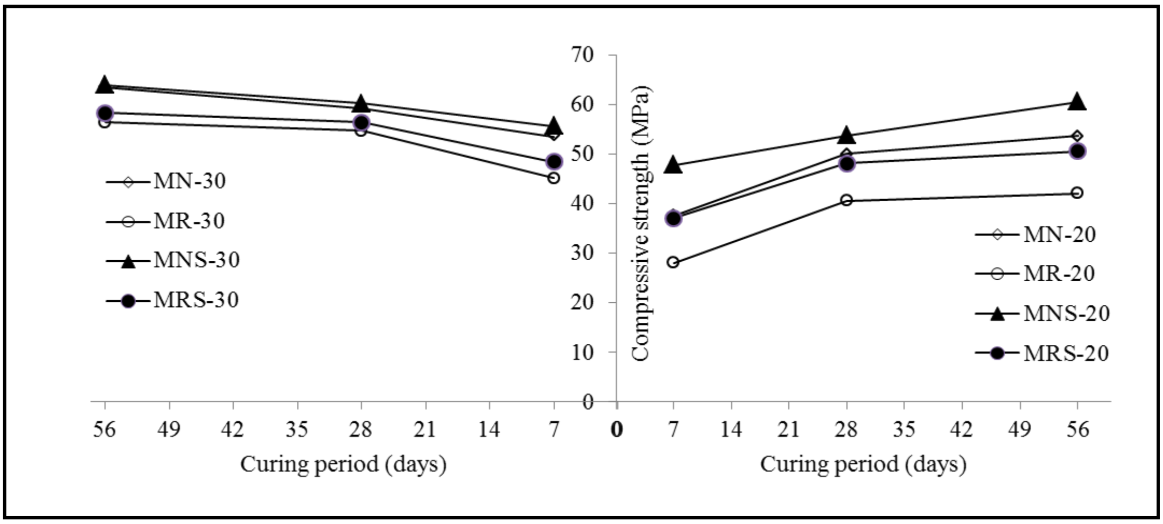


Figure 2. Development of compressive strength of concrete with and without the addition of super plasticizer for different curing periods

This indicates that the attaining of initial strength (7 days curing period) in normal concrete is relatively higher than that of recycled aggregate concrete (RAC). Further, It is observed that in medium strength concrete (MN-30 and MR-30) the initial strength gain is more when compared to normal strength concrete (MN-20 and MR-20). After 28 days of curing, no significant increase in strength is observed in recycled aggregate concrete (MR-20 and MR-30) against an increase of 7% in concrete with natural aggregate (MN-20 and MN-30). A similar observation is reported in the literature for curing age between 28 days to 90 days and 6 months [11, 13]. It is reported in the literature that the new ITZ between the cement paste and the recycled coarse aggregate has lower w/c ratio than the old ITZ between the adhered old mortar and aggregate. As a result, the new ITZ with aggregate becomes stiffer [27]. The percentage reduction in compressive strength at the age of 28 days curing in MR-20 and MR-30 are 19 and 8% respectively than those in MN-20 and MN-30. Nevertheless, both normal strength of RAC (MR-20) and medium strength of RAC (MR-30) have attained their 28 days target strength. C Rao et al. [13] have reported similar observation in the literature. This indicate that if the mix is designed properly as per IS: 10262 (2009), the recycled coarse aggregate may be used from the compressive strength point of view.

(b) Effect of Superplasticizer on compressive strength

Conplast BV 40superplasticizer is used in both normal and recycled aggregate concrete to maintain the uniform workability and improvement in compressive strength. The compressive strength test results of concrete with the addition of super plasticizer for different curing periods is presented in vide Fig. 2. It shows that irrespective of the strength of both normal and recycled aggregate concretes, the compressive strength is increased at all curing periods with the addition of superplasticizer. At 7 days of curing, the increase in compressive strength in normal strength concrete (MNS-20 and MRS-20) is 27% and 32%

respectively against an increase of 3% and 7% respectively in medium strength concrete i.e. MNS-30 and MRS-30. Similarly, after 28 days of curing, the increase in compressive strength of both MNS-20 and MRS-20 are 7% and 18% respectively when compared to an increase of 1% and 3% in MNS-30 and MRS-30 respectively. These indicates that the influence of superplasticizer is relatively more in normal strength concrete (MNS-20 and MRS-20) when compared to medium strength concrete (MNS-30 and MRS-30). It is also observed that the superplasticizer is more effective in compressive strength improvement at early age of curing in both normal and recycled aggregate concretes. After 28 days of curing, no significant increase in compressive strength is observed in both normal and medium strength concrete made with natural and recycled aggregate concrete.

The relative percentage increase in compressive strength due to the addition of superplasticizer in both normal concrete and recycled aggregate concrete are presented in Figs. 3-6.

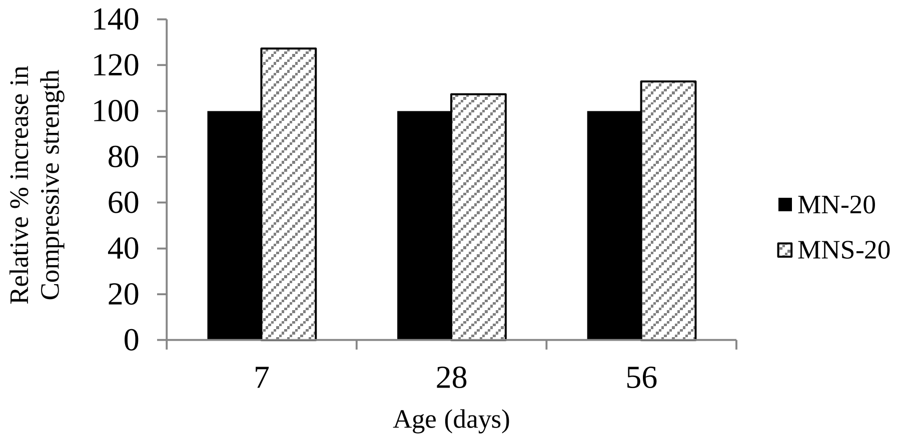


Figure 3. Relative percentage in compressive strength with curing age in normal strength concrete with natural aggregate

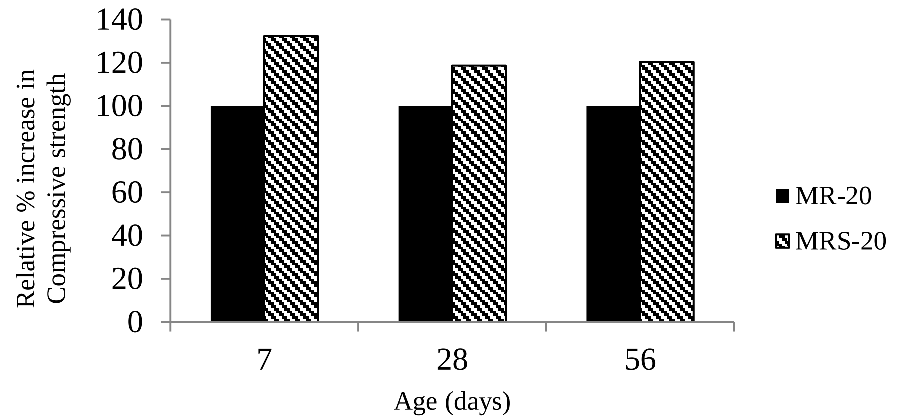


Fig.4 Relative percentage in compressive strength with curing age in normal strength concrete with recycled coarse aggregate

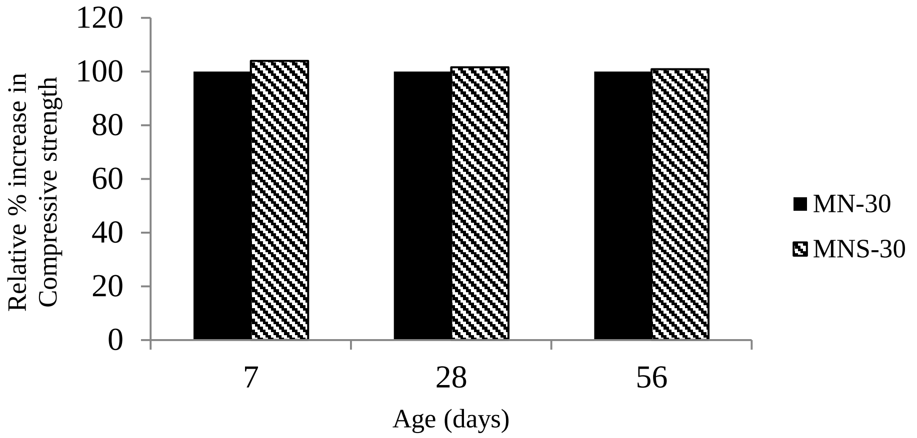


Figure 5. Relative percentage in compressive strength with curing age in medium strength concrete with natural aggregate

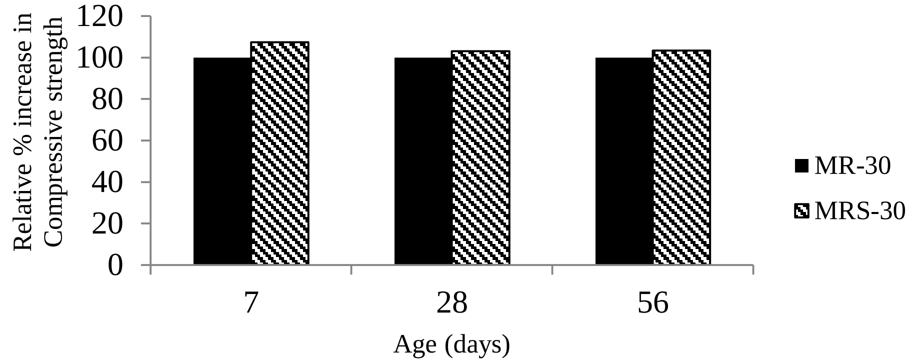


Figure 6. Relative percentage in compressive strength with curing age in medium strength concrete with recycled coarse aggregate

The Figs. shows that the gain in compressive strength at all curing periods in recycled aggregate concrete (MRS-20 and MRS-30) is more when compared to those in normal concrete (MNS-20 and MNS-30). As the water absorption of recycled coarse aggregate is more compared to natural coarse aggregate, there may be large quantity of unhydrated cement particles at the interface. But, with the addition of superplasticizer, the quality of old interfacial transition zone may improve due to more absorption capacity of old mortar which is adhered to recycled aggregates. It is also observed that with the addition of superplasticizer in RAC, it may be possible to achieve the normal and medium strength concrete as it was achieved the concrete with natural aggregate without addition of superplasticizer. Therefore the recycled coarse aggregate may be used as an alternative material for natural coarse aggregate in the production of concrete with the effective utilization of superplasticizer.

(c) Split tensile and flexural strength

The tests results of split tensile strength and flexural strength of both normal concrete and recycled aggregate concrete with and without addition of superplasticizer are presented in Table 3.

Table 3: Split tensile and flexural strength of both normal and recycled aggregate concrete with and without addition of superplasticizer

| Mix designation | Split tensile strength (MPa) | Flexural strength (MPa) |
|---|---|---|
| Without Superplasticizer | | |
| MN-20 | 3.27 | 4.69 |
| MR-20 | 2.83 | 3.56 |
| MN-30 | 4.05 | 7.74 |
| MR-30 | 3.86 | 5.94 |
| With addition of Superplasticizer | | |
| MNS-20 | 3.79 | 5.99 |
| MRS-20 | 3.17 | 4.96 |
| MNS-30 | 4.37 | 8.49 |
| MRS-30 | 4.10 | 6.76 |

It is observed that irrespective of the strength (grade) of concrete, both split tensile and flexural strengths of recycled aggregate concrete without addition of superplasticizer are less than those of normal concrete. Similar results are reported in the literature [3, 13, 28]. From the Table, it is revealed that the reduction in split tensile strength in MR-20 and MR-30 is 4.5% and 13% respectively when compared to the corresponding normal concrete i.e. MN-20 and MN-30. Similarly the percentage reduction in flexural strength of MR-20 and MR-30 are 16% and 23% respectively than those of corresponding normal concrete. This may be due to the weaker interfacial transition zone (ITZ) between old cement mortar and aggregate, which may also be due to poor mechanical characteristics of recycled coarse aggregate. Table also reveal that the split tensile strength is around 7% of that of corresponding compressive strength in both normal and recycled aggregate concrete and the flexural strength is around 10-13% and 9-10% of that of the corresponding compressive strength in normal concrete and recycled aggregate concrete respectively. In general the split tensile strength and flexural strength of concrete are in the order of 10% and 15% of compressive strength respectively for normal concrete.

(d) Influence of Superplasticizer

The test results of split tensile and flexural strength of both normal and recycled aggregate concrete after addition of superplasticizer are presented in vide Table 3. It reveals that there is an improvement in both split tensile and flexural strength of both normal concrete and recycled aggregate concrete. Nevertheless, the split tensile and flexural strength of MRS-20 and MRS-30 are less than those of MNS-20 and MNS-30 respectively. The relative percentage increase in split tensile and flexural strength in both normal and recycled aggregate concrete with the addition of superplasticizer are presented in Figs.7 and 8 respectively.

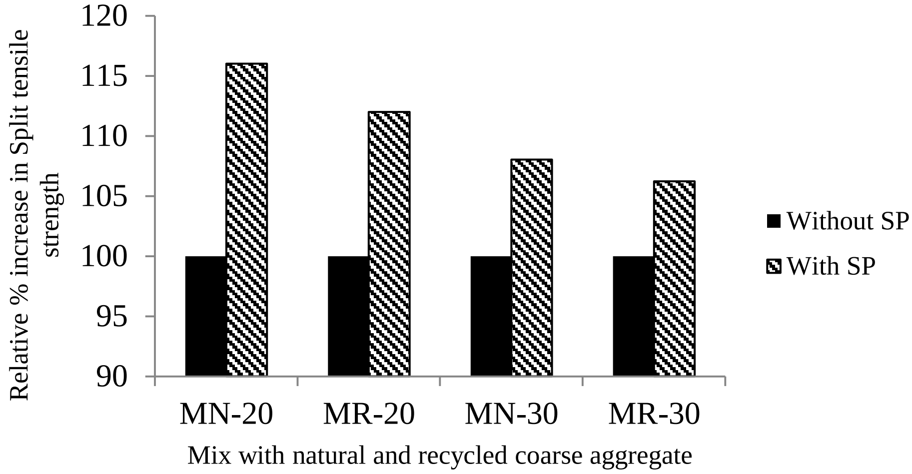


Figure 7. Relative percentage of split tensile strength in both normal and recycled aggregate concrete with the addition of superplasticizer

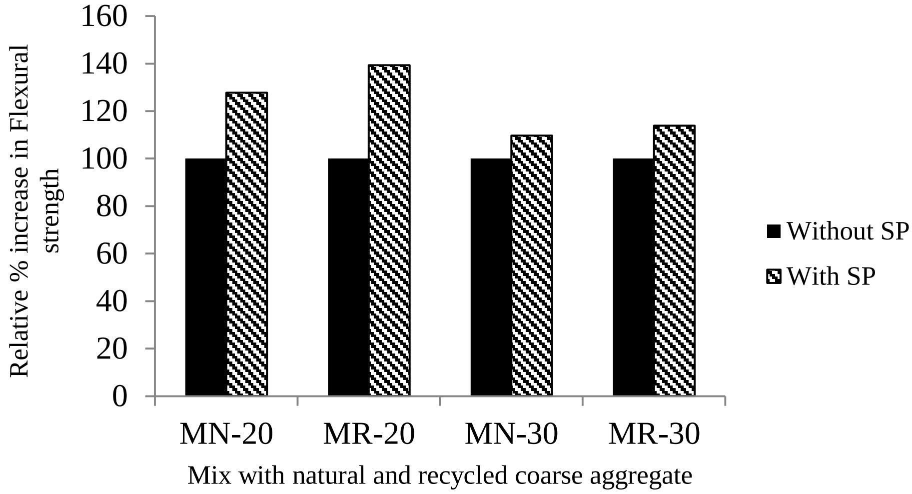


Figure 8. Relative percentage of flexural tensile strength in both normal and recycled aggregate concrete with the addition of superplasticizer

The Figs. shows that the superplasticizer is more effective in development of split tensile and flexural strength in normal strength concrete with both natural (MNS-20) and recycled coarse aggregate (MRS-20) compared to those of medium strength concrete (MNS-30 and MRS-30). There is approximately 16-13% increase in split tensile strength in normal strength concrete (MNS-20 and MRS-20) against 8-6% in medium strength concrete (MNS-30 and MRS-30). In case of flexural strength, this increase is relatively more: in normal strength concrete (MNS-20 and MRS-20) the increase is approximately 27-39% and in medium strength concrete (MNS-30 and MRS-30), it is around 10-13%.

(e) Stress-strain characteristics

The stress-strain variation of normal strength concrete and medium strength concrete with natural and recycled coarse aggregate without addition of superplasticizer is presented in Fig. 9. It reveals that the trend is almost similar in all the mixes of concrete. In addition, in case of recycled aggregate concrete of both normal strength (MR-20) and medium strength (MR-30), at an applied stress the strain increases at a faster rate than those of corresponding normal concrete. Therefore, the curvature of the stress strain curve continues to increase in case of RAC. This may be due to the presence of finer cracks at the interfaces between old cement mortar and aggregate. These interfaces help the cracks to propagate further during loading.

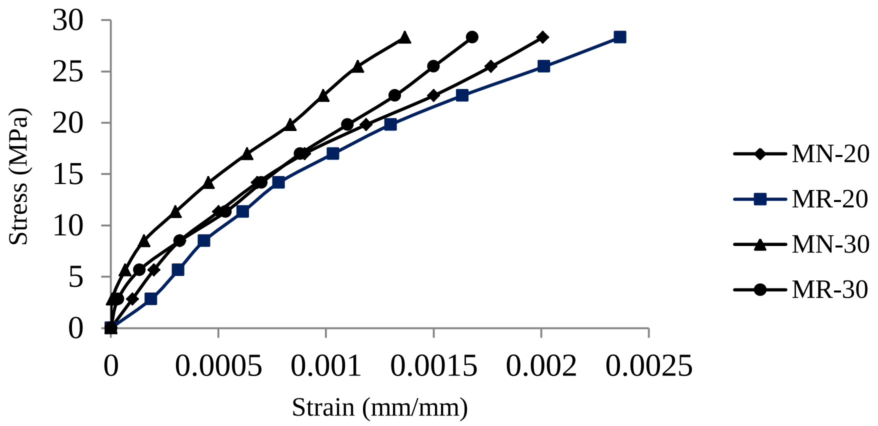


Figure 9. Stress-strain variation of both normal and medium strength concrete with natural and recycled coarse aggregate without addition of superplasticizer

(f) Influence of superplaticizer on stress-strain characteristics

The stress-strain variation of normal strength concrete and medium strength concrete with natural and recycled coarse aggregate with the addition of superplasticizer are presented in Figs. 10 and 11 respectively.

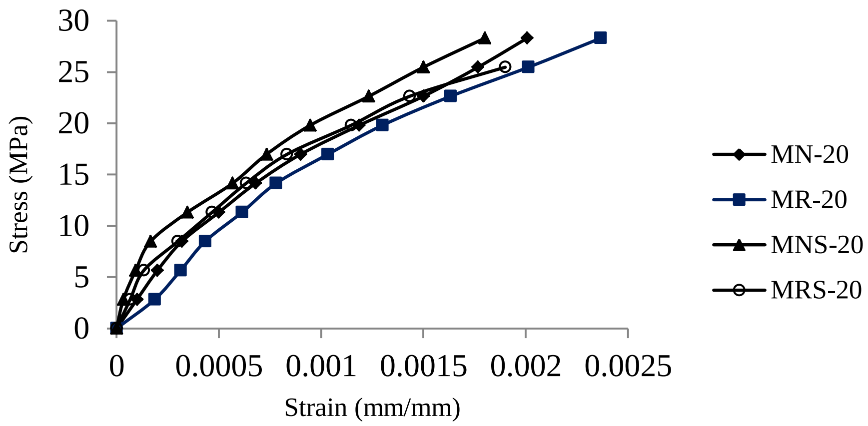


Figure 10. Influence of superplasticizer on Stress-strain variation of normal strength concrete

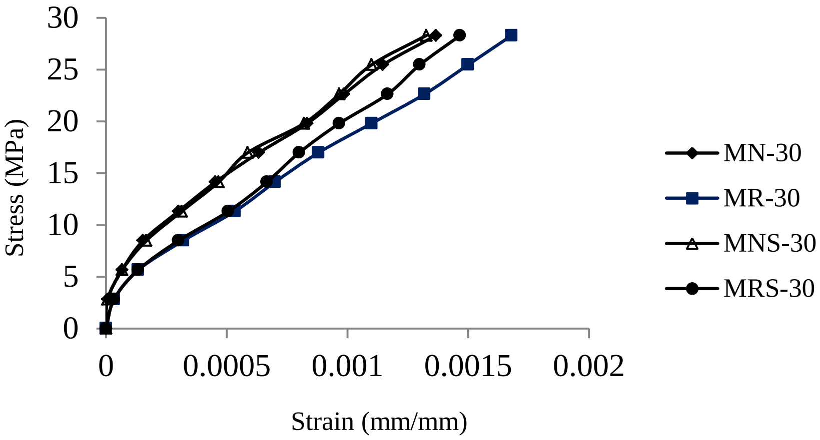


Figure 11. Influence of superplasticizer on Stress-strain variation of medium strength concrete

Figs. shows that a similar trend is observed in both normal and recycled aggregate concrete with the addition of superplasticizer, as it was observed in concrete without superplasticizer, In addition, it is observed that at an applied stress, the strains are reduced in both normal and medium strength concrete with natural and recycled aggregate when compared to those without superplasticizer. That is the deformation characteristics are relatively improved with the addition of superplasticizer. Nevertheless, in RAC of both normal strength (MRS-20) and medium strength (MRS-30) concrete, at an applied stress the strain increases at a faster rate than those of corresponding normal concrete i.e. the deformation characteristics are relatively poor in RAC compared to NAC even after addition of superplasticizer.

## 6. NON-DESTRUCTIVE TEST RESULTS

(a) Rebound number

The rebound hammer test is conducted as per the procedure given in BIS(IS: 13311-1992 (Part 2)). It is classified as hardness test and it is based on the principle that the rebound of an elastic mass depends on the surface hardness against which the mass impinges. It measures only the surface zone properties. The test results of rebound number for both normal strength concrete (MN-20 and MR-20) and medium strength concrete (MN-30 and MR-30)) with natural coarse aggregate and recycled coarse aggregate without addition of superplasticizer for different curing periods is presented in Fig. 12.

It is observed that, irrespective of the strength of concrete the rebound number increased with the curing period. This is due to increase in strength of concrete with further hydration of the cement. The results also shows that in both normal and medium strength concrete, use of recycled coarse aggregate instead of natural aggregate reduced the rebound number due to the increased porosity of concrete as the result of using more porous nature of aggregate due to weak cement paste that is adhered to them. At the age of 28 days, the rebound number for normal concrete is 28 to 31, whereas, the same for RAC is 26 to 28 in normal and medium strength concrete respectively.

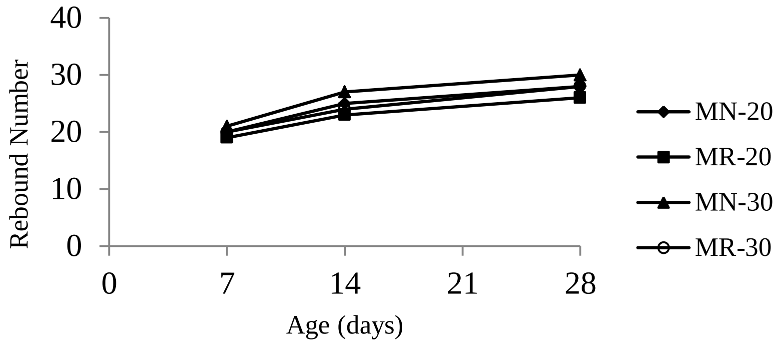


Figure 12. Variation of rebound number at different curing periods in both normal and medium strength concrete with natural and recycled aggregates

(b) Influence of Super plasticizer

Figs. 13 and 14 shows the test results of rebound number for both normal strength concrete and medium strength concrete with natural coarse aggregate (MN-20 and MN-30) and recycled coarse aggregate (MR-20 and MR-30) after addition of superplasticizer for different curing periods.

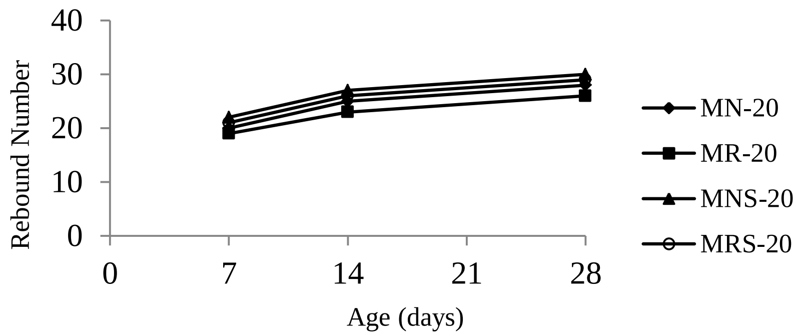


Figure 13. Variation of rebound number at different curing periods of normal strength concrete with both natural and recycled aggregate with addition of superplasticizer

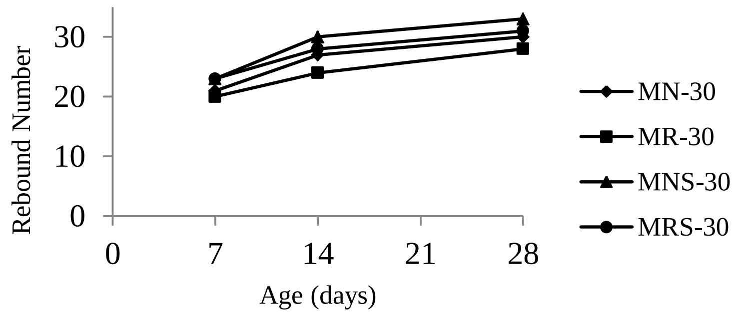


Figure 14. Variation of rebound number at different curing periods of medium strength concrete with both natural and recycled aggregate with addition of superplasticizer

It is observed that irrespective of the strength of concrete i.e. normal and medium, the rebound number of both normal concrete and recycled aggregate concrete are increased with the addition of superplasticizer when compared to those without superplasticizer at all curing periods. It also observed that the increase is relatively more in recycled aggregate concrete when compared to normal concrete. This may be due to high absorption capacity of recycled aggregate, with the addition of superplasticizer there may be an improvement in the strength of old ITZ. At the age of 28 days, the rebound number for normal concrete with superplasticizer (MNS-20 and MNS-30) is 30and 33 respectively against 28 and 30 without superplasticizer (MN-20 and MN-30). Similarly the rebound number of RAC with superplastizer (MRS-20 and MRS-30) is 29 and 31 respectively against to 26 and 28 in concrete without superplasticizer i.e. MR-20 and MR-30 respectively.

(c) Relationship between Compressive strength and Rebound Number

Fig. 15 shows the compressive strength is a function of rebound number. A regression analysis between compressive strength and rebound number is carried out to obtain a correlation coefficient equal to 0.72 by using a power model which is the best fitted for the relationships under study. The obtained relationship is indicated in Eqn.1.

$$\text{Compressive strength} \quad f_{ck} = 0.312 \times N^{1.517} \quad (R^2 = 0.72) \tag{1}$$

Where $f_{ck}$ is in MPa and N is a number.

It reveals that the compressive strength decreased with the decrease in rebound number.

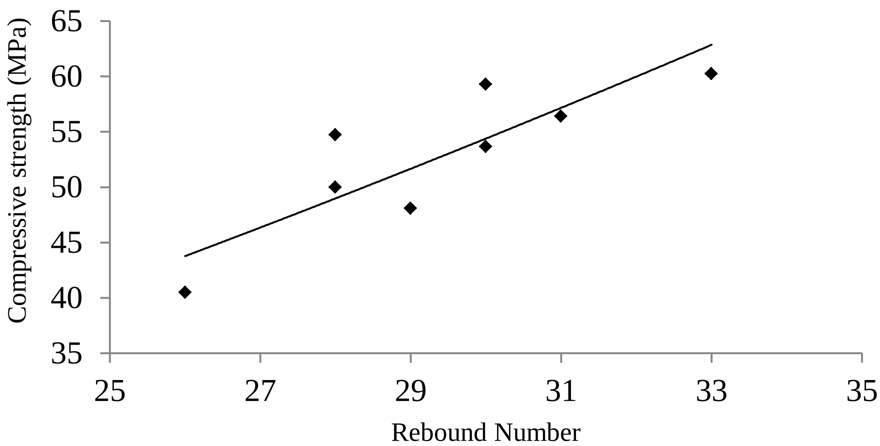


Figure 15. Compressive strength is a function of rebound number

(d) Ultrasonic Pulse Velocity

The effect of curing on the development of ultrasonic pulse velocity of both normal concrete and recycled aggregate concrete with curing age is presented in Fig. 16.

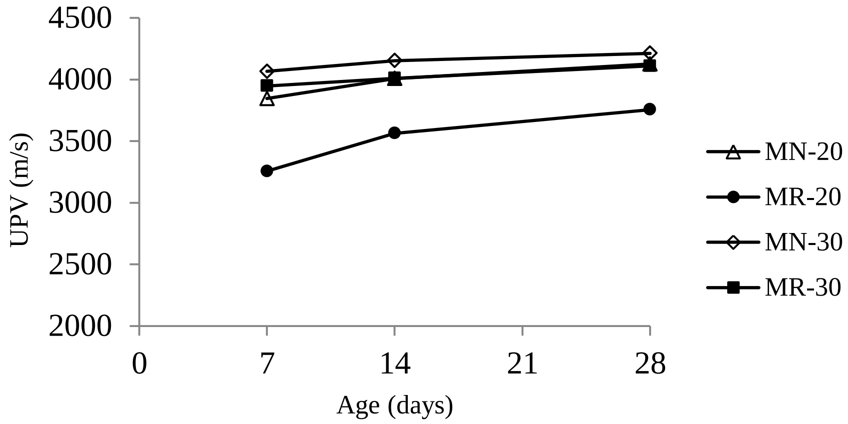


Figure 16. Development of Ultrasonic pulse velocity of both normal and recycled aggregate concrete with curing period

It is observed that the pulse velocity of both normal concrete and recycled aggregate concrete are increased with the curing age. This may be due to the reduction in capillary porosity with further increase in the rate of hydration with the curing period. When the degree of hydration of cement increases with age, the capillary porosity of hardened cement paste decreased causing the increase in pulse velocity of concrete. It is also observed that the ultrasonic pulse velocity of both normal and medium strength concrete with recycled coarse aggregate (MR-20 & MR-30) is lower than those of with natural aggregate at all curing periods. This may be due to the change in porosity of recycled coarse aggregate and the presence of more number of micro cracks in recycled aggregate. The recycled aggregate generally consist of strong natural aggregate with more porous cement mortar attached to them. Similar results are reported in the literature [29-30]. After 28 days of curing the UPV of normal and medium strength concrete with recycled aggregate i.e. MR-30 and MR-20 are 4.11 and 3.75 km/s respectively against 4.12 and 4.21 km/s of the corresponding normal concrete i.e. MN-20 and MN-30 respectively. This indicates the uniformity of concrete mixes. According to IS: 13311-1992 (Part 1), the quality of concrete graded as excellent and good when the pulse velocity is more than 4.5 km/s and 3.5 to 4.5 km/s respectively. The pulse velocity through a good-quality mortar is found to vary between 3.50 to 3.95 km/s, whereas that through granite is about 4.60 km/s or more. Thus, it is not surprising to obtain a lower pulse velocity for recycled aggregate concrete having a similar volumetric mix composition to that of natural aggregate concrete.

(e) Influence of Super plasticizer

The development of ultrasonic pulse velocity (UPV) in normal strength concrete with both natural and recycled coarse aggregate after addition of superplasticizer with curing age are presented in Fig. 17.

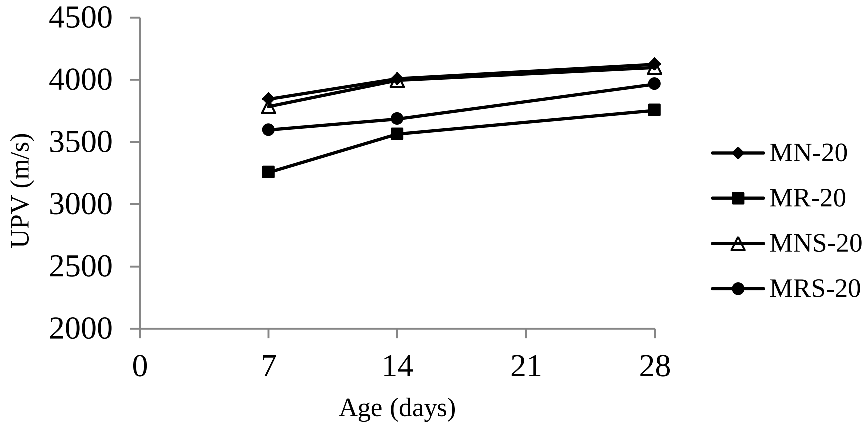


Figure 17. Development of Ultrasonic pulse velocity of normal strength concrete with superplasticizerat different curing periods

Similarly, the development of UPV in medium strength concrete with curing period after addition of superplasticizer is presented in Fig. 18.

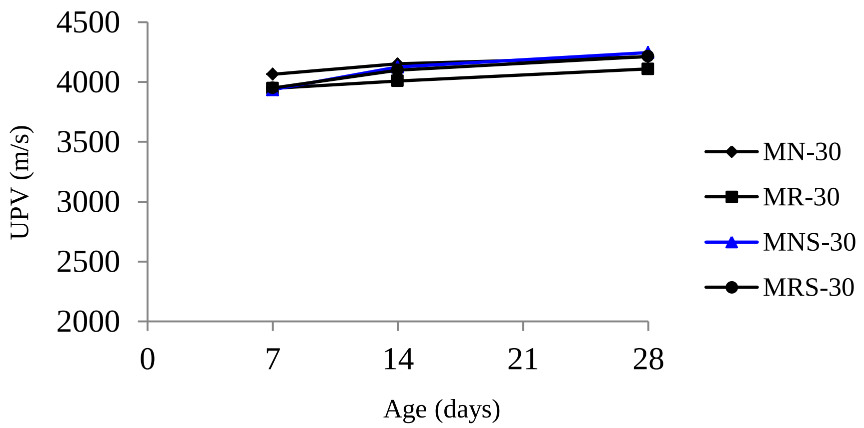


Figure 18. Development of ultrasonic pulse velocity of medium strength concrete with superplasticizerat different curing periods

The Figs. reveals that the development trend of UPV with curing age is almost similar trend in both normal and recycled aggregate concrete with and without addition of superplasticizer. The Figs. also reveal that the influence of superplasticizer is relatively more in case of normal strength concrete with recycled coarse aggregate (MRS-20) compared to medium strength concrete with RCA (MRS-30). At the age of 28 days of curing, the UPV of MRS-30 and MRS-20 are 4.21 and 3.96 km/s against 4.11 and 3.75 km/s of MR-30 and MR-20 respectively. Similarly the UPV of concrete with natural aggregate i.e. MNS-30 and MNS-20 are 4.25 and 4.06 km/s compared to 4.2 and 4.1 of MN-30 and MN-20 respectively. This indicates that the effect of superplasticizer is not much significant in development of UPV in normal concrete.

The variation in pulse velocity under compressive stress for normal and medium strength concrete with both natural and recycled coarse aggregate with and without addition of superplasticizer is presented in Figs. 19 and 20 respectively. It is observed that irrespective of the strength of concrete i.e. normal and medium, the variation in pulse velocity under stress is almost similar in both normal concrete and recycled aggregate concrete with and without addition of superplasticizer. Further, it reveals that the pulse velocity increases with the increase in stress up to 4-5 MPa and then it is constant with further increase in stress up to 17 to 20 MPa and thereafter starts decrease with further increase in stress up to failure. The initial increase in velocity may be due to restructuring of the internal microcracks in the material.

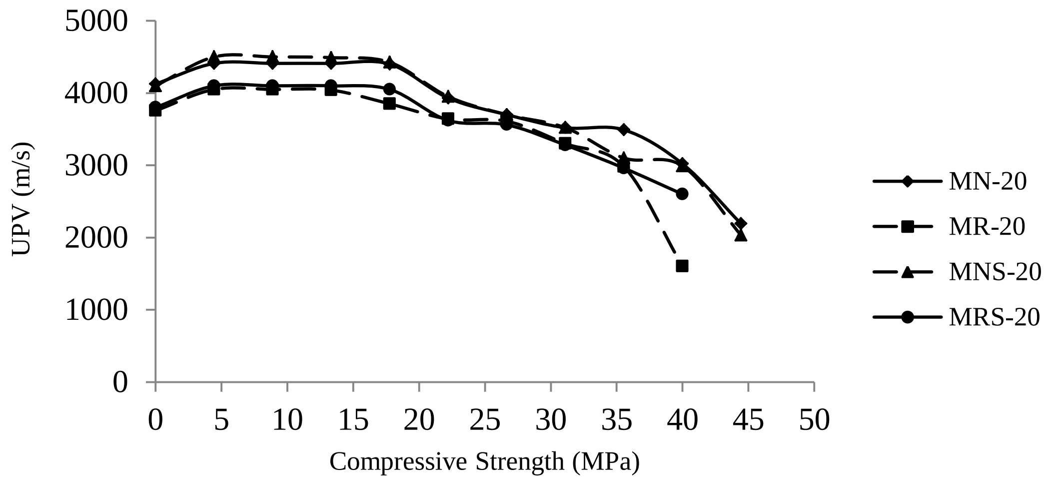


Figure 19. Ultrasonic pulse velocity variation under stress for normal strength concrete with natural and recycled aggregate with and without addition of superplasticizer

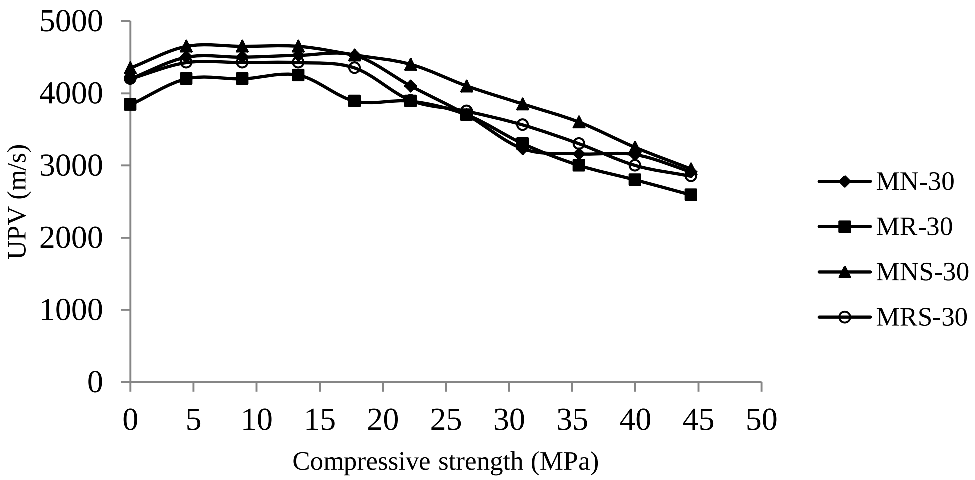


Figure 20. Ultrasonic pulse velocity variation under stress for medium strength concrete with natural and recycled aggregate with and without addition of superplasticizer

As the load increases these microcracks gets widened and the velocity is reduced. At the time of failure the drop in velocity is higher in case of RAC when compared to normal concrete. Similar observations are reported in the literature [30].

(f) Relationship between Compressive strength and Pulse velocity

The compressive strength of concrete is one of the prime properties of structural concrete. Hence, the strength and pulse velocity relation is obtained from the experimental results and is presented in Fig.21.

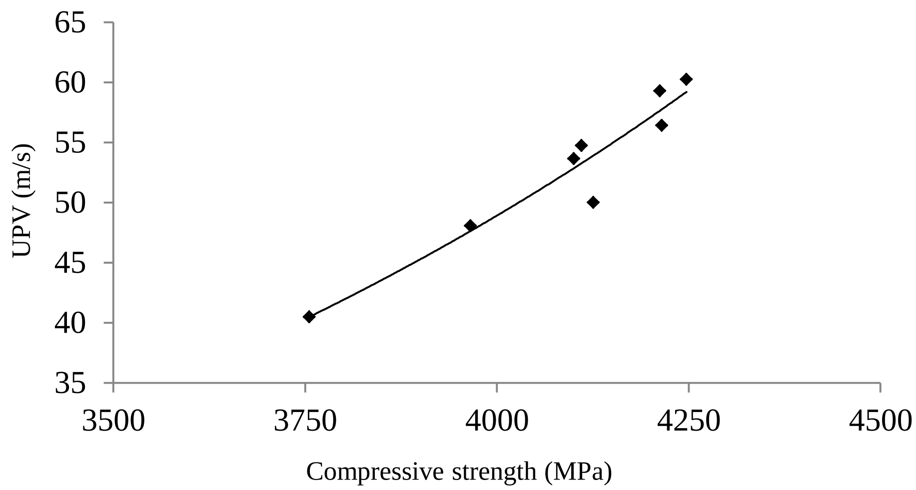


Figure 21. Compressive strength is a function of pulse velocity

It is observed that the compressive strength is decreased with the decrease in pulse velocity. A regression analysis between compressive strength and pulse velocity is performed to obtain a correlation coefficient $R^2$equal to 0.93 by using exponential model which is the best fitted curve for the relationship under study. The obtained relationship is indicated in Eqn.2 for compressive strength ($f_{ck}$) and pulse velocity (V).

$$\text{Compressive strength} \quad f_{ck} = 2.221 \times e^{0.0008 \times V} \quad (R^2 = 0.93) \tag{2}$$

Where $f_{ck}$ is in MPa,and V is in m/s.

## 7. CONCLUSIONS

- Porous and rough nature of surfaces, generated due to the presence of adhered mortar on recycled coarse aggregate, help in developing better bond though water requirement is 4.6 times higher than the natural aggregates for achieving desired workability. Also, due to the adherence of mortar the specific gravity and bulk density of RCA are reduced when compared to natural aggregate.
- Workability of recycled aggregate concrete is less in comparison to the concrete made with natural aggregates. The reason for this may be attributed to the porous and rough

surfaces of the recycled aggregates stated above. Superplasticizer influences the workability of both normal and recycled aggregate concrete significantly.

- If the mix is designed properly as per IS: 10262 (2009), the recycled aggregate concrete could be achieved its 28 days target strength even though the compressive strength of recycled aggregate concrete is lower than that of normal. The compressive strength of RAC could be enhanced significantly with the addition of superplasticizer. Further, with the addition of superplasticizer in RAC, it may be possible to achieve the normal and medium strength concrete as it is achieved the same with natural aggregate without addition of superplasticizer.
- The tensile strength of RAC is lower than that of concrete with natural aggregate. This is apparently because of poor mechanical strength of recycled coarse aggregates. However, these strengths may be improved with the effective utilization of superplasticizer.
- The pulse velocity and rebound number of RAC in both normal and medium strengths are lower than those of corresponding normal concrete. Nevertheless, the results of pulse velocity of RAC indicate the quality of concrete is good. The quality of RAC is further improved with the addition of superplasticizer. The stress level in concrete influences the pulse velocity of both normal and medium strength concrete with natural and recycled coarse aggregate. The rebound number and pulse velocity are related with compressive strength using power and exponential best fit curves respectively. However, more data is required to make the exact relationship among these properties.

## REFERENCES


1. Frondistou-Yannas S. Waste concrete as aggregate for new concrete, *Journal of American Concrete Institute*, **74**(1977) 373-6.
2. Hansen TC, Narud H. Strength of recycled concrete made from crushed concrete coarse aggregate, *Concrete International – Designand Construction*, **5**(1983) 79-83.
3. Bairagi NK, Kishore R, Pareek VK. Behaviour of concrete with different proportions of natural and recycled aggregates, *Resources, Conservation and Recycling*, **9**(1993) 109-26.
4. Limbachiya MC, Leelawat T, Dhir RK. Use of recycled concrete aggregate in high strength concrete, *Materials and Structures*, **33**(2000) 574-80.
5. Ajdukiewicz A, Kliszczewicz A.Influence of recycled aggregates on mechanical properties of HS/HPC, *Cement and Concrete Composites*, **24**(2002) 269-79.
6. Poon CS, Shui ZH, Lam L, Fok H, Kou SC. Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of concrete, *Cement and Concrete Research*, **34**(2004) 31-6.
7. Rao A, Jha KN, Misra S. Use of aggregates from recycled construction and demolition waste in concrete, *Resources, Conservation and Recycling*, **50**(2006) 71-81.
8. Rahal K. Mechanical properties of concrete with recycled coarse aggregate, *Building and Environment*, **42**(2007) 407-15.

9. Etxeberria M, Vazquez E, Mari A, Barra M. Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete, *Cement and Concrete Research*, **37**(2007) 735-42.
10. Yang KH, Chung HS, Ashour AF. Influence of type and replacement level of recycled aggregates on concrete properties, *ACI Materials Journal*, **105**(2008) 289-96.
11. Kou SC, Poon CS. Mechanical properties of 5-year–old concrete prepared with recycled aggregates obtained from three different sources, *Magazine of Concrete Research*, **60**(2008) 57-64.
12. Padmini AK, Ramamurthy K, Mathews MS. Influence of parent concrete on theproperties of recycled aggregate concrete, *Construction and Building Materials*, **23** (2009) 829-36.
13. C Rao M, Bhattacharyya SK, Barai SV. Influence of field recycled coarse aggregate on the properties of concrete, *Materials and Structures*, **44**(2011) 205-20.
14. Elhakam AB, Mohamed AE, Awad E. Influence of self-healing, mixing method and adding silica fume on mechanical properties of recycled aggregates concrete, *Construction and Building Materials*, **35**(2012) 421-7.
15. Kou CS, Poon CS, Agrela F. Comparisons of natural and recycled aggregate concretes prepared with the addition of different mineral admixtures, *Cement and Concrete Composites*, **33**(2011) 788-95.
16. Kou CS, Poon CS. Long term mechanical and durability properties of recycled aggregate concrete prepared with the incorporation of fly ash, *Cement and Concrete Composites*, **37**(2013) 12-9.
17. Katz A. Treatments for the improvement of recycled aggregate, *Journal of Materials in Civil Engineering*, *ASCE*, **16**(2004) 597-603.
18. Tam VWY, Gao XF, Tam CM. Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach, *Cement and Concrete Research*, **35**(2005) 1195-1203.
19. Tam VWY, GaoXF, Tam CM. Comparing the performance of modified two-stage mixing approach for producing recycled aggregate concrete, *Magazine of Concrete Research*, **58**(2005) 477-84.
20. Tam VWY, Tam CM, Le KN. Removal of cement mortar remains from recycled aggregate using pre-soaking approach,*Resources, Conservation and Recycling*, **50** (2007) 82-101.
21. Tam VWY, Tam CM. Diversifying two-stage mixing approach (TSMA) for recycled aggregate concrete: TSMAS and TSMASC, *Construction and Building Materials*, **22** (2008) 2068-77.
22. Li J, Xiao H, Zhou Y. Influence of coating recycled aggregate surface with pozzolanic powder on properties of recycled aggregate concrete, *Construction and Building Materials*, **23**(2009) 1287-91.

23. Matias D, De Brito J, Rosa A, Pedro D. Mechanical properties of concrete produced with recycled coarse aggregates-Influence of the use of superplasticizers, *Construction and Building Materials*, **44**(2013) 101-9.
24. Pereira P, Evangelista L, De Brito J. The effect of superplasticizers on the mechanical performance of concrete made with fine recycled concrete aggregates, *Cement and Concrete Composites*, **34**(2012) 1044-52.
25. Works Bureau. Works Bureau Technical Circular 12/2002, Specifications facilitating the use of recycled aggregates, Hong Kong SAR Government,2002.
26. Shanghai Construction Standard Society (SCSS). Technical Code for Application of Recycled Aggregate Concrete (DG/TJ07-008), Shanghai, 2007.
27. Etxeberria M, Vazquez E, Mari ER. Microstructure analysis of hardened recycled aggregate concrete, *Magazine of Concrete Research*, **58**(2006) 683-90.
28. Limbachiya M, Meddah MS, Ouchagour Y. Performance of portland/silica fume cement concrete produced with recycled concrete aggregate, *ACI Materials Journal*, **109**(2012).
29. Ravindrarajah R, Loo YH, Tam CT. Strength evaluation of recycled aggregate concrete by in-situ tests, *Materials and Structures*, **21**(1988) 289-95.
30. C Rao M, Bhattacharyya SK, Barai SV. Testing of recycled aggregate concrete by non-destructive tests, *International Journal of Structural Engineering and World Congress (IJSEW)*, March, 2012.