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Punching shear behavior of recycled aggregate concrete

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Abstract. Flat-slabs, being a significant structural component, not only reduce the dead load of the structure but also reduce the amount of concrete required for construction. Moreover the use of recycled aggregates lowers the impact of large scale construction to nearby ecosystems. Recycled aggregate based concrete being a quasi-brittle material shows enormous cracking during failure. Crack growth in flat-slabs is mostly in sliding mode (Mode II). Therefore sufficient sections need to be provided for resistance against such failure modes. The main objective of the paper is to numerically determine the ultimate load carrying capacity of two self-similar flat-slab specimens and validate the results experimentally for the natural aggregate as well as recycled aggregate based concrete. Punching shear experiments are carried out on circular flat-slab specimen on a rigid circular knife-edge support built out of both normal (NAC) and recycled aggregate concrete (RAC, with full replacement). Uniaxial compression and bending tests have been conducted on cubes, cylinders and prisms using both types of concrete (NAC and RAC) for its material characterization and use in the numerical scheme. The numerical simulations have been conducted in ABAQUS (a known finite element software package). Eight noded solid elements have been used to model the flat slab and material properties have been considered from experimental tests. The inbuilt Concrete Damaged Plasticity model of ABAQUS has been used to monitor crack propagation in the specimen during numerical simulations.

Keywords: punching shear; flat slabs; Mode II crack propagation; recycled aggregate concrete

1. Introduction

Design of concrete structures has always been a challenge for engineers because of material heterogeneity and anisotropy. Standard design philosophies which are followed all over the world are primarily based on various assumptions of concrete behavior under different loading situations. Slabs (one way and two way) being intricate structural components is designed primarily considering flexure, for which reinforcement in provided, while sections are assumed to be self-sufficient in resisting shear. This conceptualizes the use of flat-slabs which primarily transfer load by shear. Concrete being a quasi-brittle material shows enormous cracking during failure. Crack growth in flat-slabs is mostly in sliding mode (Mode II). The present study focuses on the behavior of NAC and RAC when loaded in shear. Numerical simulations have been carried out in ABAQUS and validated with experiments. Different sizes of the model have been used to study the size-effect of concrete. The material parameters of concrete have been evaluated from experiments on cubes, cylinders and prisms. This work ultimately concludes by offering the shear carrying capacity of a given concrete section when it is subjected to Mode II fracture.

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1.1 Basics of flat-slabs

In general normal frame construction utilizes columns, slabs and beams. However it might be possible to undertake construction without providing beams. In such a case the frame system would consist of a slab and column but without beams. These types of slabs are called flat-slabs, since their behavior resembles the bending of flat-plates. The key components of flat slabs are drops and capitals. Drop panels are provided to resist the punching shear which is predominant at the contact of slab and column. Capitals are provided for negative moment transfer from the slab to the column (Sahab *et al*. 2005).

The basic design philosophy behind flat-slabs is the resistance against punching shear. Therefore once the mode of failure gets determined, the capacity of the slab comes down to the evaluation of the shear capacity of concrete being used. It is very difficult to evaluate the shear strength of concrete and hence numerical simulations are often used to validate complex models. Fig. 1 shows the different parts of a flat-slab system.

1.2 Recycled building materials

1.2.1 Waste concrete

Environment protection is the key to all lifesaving activities in the modern world. Increase in population has led to a substantial depletion of resources and increase in pollution. The construction industry is one such source of massive waste production to the ecology. Consciousness towards protection of natural resources and sustainable development should be a major concern in the era. India

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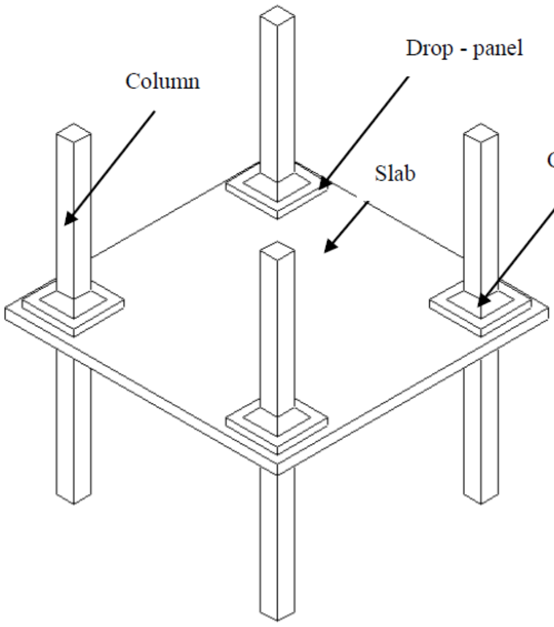


Fig. 1 Flat-slab along with its components

being a developing nation has invested a lot in its large scale urbanization leading to huge quantities of demotion of infrastructures. This has led to the accumulation of huge quantities of construction and demolition wastes which amounts to around 30%-40% of total wastes generated annually. Since a large portion of construction waste comes out of concrete, it is beneficial to reuse this waste as recycled coarse aggregate. It is estimated that more than 1 billion tons of waste concrete are currently produced annually in the world and this figure is very likely to go up with time. Moreover, natural disasters also produce huge amounts of waste concrete. Thus the need of recycling waste concrete is highly necessary from the environment point of view. Production of recycled aggregate concrete has been recognized as a satisfactory approach in recycling waste concrete and achieving sustainable development in the construction industry (Xiao *et al*. 2011).

1.2.2 History and developments in concrete recycling

The notion of recycling aggregates for concrete production was conceptualized in China about 15 years ago. A review report by Xiao *et al*. (2011) was published where the benefits of RAC and its impact on the environment has been recognized by more and more construction professionals in China. In the last 10 years, over 30 universities and institutes have been working on the developments of RAC. Till date, extensive experimental studies have been carried out on the material and physical properties of RCA, mix-design of RAC, as well as the applications of RAC in construction. Based on the research findings, a regional technical code for “Technical code for application of recycled concrete” (DG/TJ08-2018-2007) was issued in Shanghai. In addition, two symposiums on RAC have been held. Also the 2nd International Conference on Waste Engineering and Management, which was organized by the China Civil Engineering Society (CCES), the Hong Kong Institution of Engineers (HKIE), The Canadian Society for Civil Engineering (CSCE) and Tongji University, focused a lot on the reuse of waste construction materials and was heavily appraised (Xiao *et al*. 2011).

Cost-effective construction is the requirement of the century. In this era when development is at its peak and the construction industry in its boom, reduction in one of the major liabilities of any institution is always preferred.

1.3 Concrete characterization and concrete modeling

Concrete is one of the most complex building materials in terms of understanding its behavior under the action of various loads. Material properties of concrete are very diverse and often a very detailed material modeling technique is required to visualize its behavior. The most popular method of modeling material properties of concrete is by homogenization and is developed by testing numerous samples in compression and tension (Popovics 1973, Wang and Tsu 2001). These are some of the very basic concrete models and are very effective in evaluating the global response of concrete samples. These models have widely been used in the field of fracture mechanics and have provided very promising numerical simulations Byung *et al.* (2005), Proft *et al* (2004) showed numerical analysis of concrete structures based on fracture models. Detailed models for concrete even to the meso-level (Cusatis *et al*. 2011, Chen *et al*. 2012) are now being used for more detailed analysis of concrete specimens. Hence there is a wide range of available tools which can be used to model concrete properties.

Concrete structure design is usually based on simple analogies of concrete behavior. Working Stress Methods and Limit State Methods are based on elastic and elasto-plastic nature of concrete (IS 456 2000). More detailed behavioral analyses can be done but that would require massive computational efficiency. Concrete structures can be categorized mainly on the basis of the type of resistance it provides. These include *compression, tension, bending, shear* and *torsion* for which different analysis techniques and different design philosophies are implemented.

1.3.1 Concrete in compression

Concrete is the most commonly used material for resistance in compression. It is easy to place and the mix can be designed as per the compressive strength required. The behavior differs when the specimen in placed under confinement and shows higher strength and ductility. The compressive strength is usually achieved due to the presence of aggregates and the cement helps in binding all the aggregate particles together. There are several existing theories behind failure of concrete in compression (Ottosen 1977). Concrete cylinders and cubes are cast and tested for determination of compressive strength in concrete.

1.3.2 Concrete in tension

Concrete is very weak in tension. All failure in concrete is in some way related to tensile failure (Ottosen 1977). This is the reason behind providing tensile reinforcement in tension carrying regions of concrete structures. The behavior is mostly linear till the failure stress after which it has a long tail which is dependent on the fracture energy of

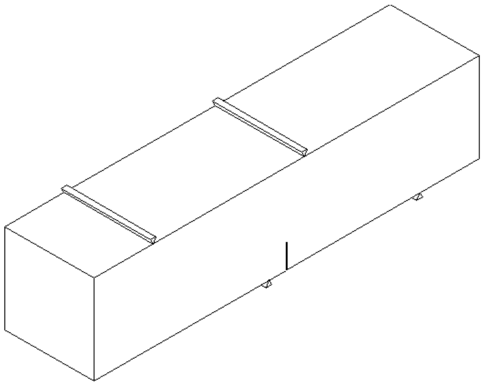


Fig. 2 Four-point shear test in concrete

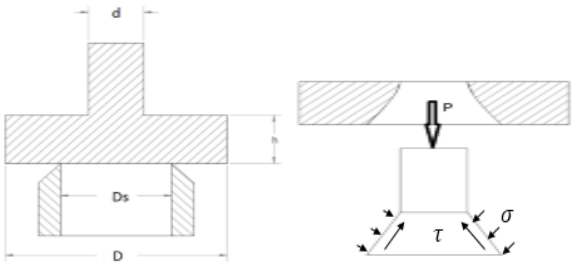


Fig. 3 Free-body diagram of the problem

concrete. Tensile strength is obtained by the split cylinder test.

1.3.3 Concrete in bending

Bending is a phenomena in which the top fiber is in compression while the bottom finer is in tension. Since concrete performs well in compression failure in the top fiber usually does not occur. The bottom needs to be reinforced with steel bars so that even when tensile cracks develop, the section is adequate enough to take additional loads. Flexural behavior is observed by 3 and 4 point bending tests on prisms.

1.3.4 Concrete in shear

Concrete shows similar properties in shear. It mainly fails due to sliding action. However there are discrepancies among researchers as an element in pure shear can be oriented in orthogonal compression and tension. Therefore separately studying the behavior of concrete in shear will not yield much result. However distinguished Mode II crack propagation is very often seen (as in this project). Pure shear tests are difficult to carry out as the specimen also gets loaded n flexure. A 4 point shear test with a notch is usually performed to check for shear strength. Fig. 2 shows the experimental setup.

1.3.5 Concrete in torsion

In torsion an element is in a state of pure shear. Torsion tests in concrete is a major challenge as thin-walled tubular structures with concrete is difficult to cast. Therefore design against torsion is done using empirical techniques (IS 456 2000) and various combinations along with bending are assumed.

This section provided a brief insight into the background of flat-slabs, usages of recycled aggregate into concrete and methods of concrete modeling. These techniques are required for a deeper insight into design of structures. It has also briefly discussed about the behavior of concrete in some of the most common loading conditions and the nature of tests required for evaluating the behavior in similar situations. The goal of the present paper is to numerically determine the ultimate load carrying capacity of two self-similar flat-slab specimens and validate the results experimentally. The paper will address following various aspects in detail.

• Comparison of ultimate load carrying capacities achieved from experiments and from numerical simulations.
• Comparison of behavior of flat-slab specimens with natural aggregate concrete and recycled aggregate concrete.
• Evaluating the variation of shear stress in specimens of different sizes, mixes and source of aggregate in concrete.
• Achievement of size-effect characteristics in concrete of different mix and casted with different source of aggregates.

2. Crack propagation in concrete: Background and modelling aspects

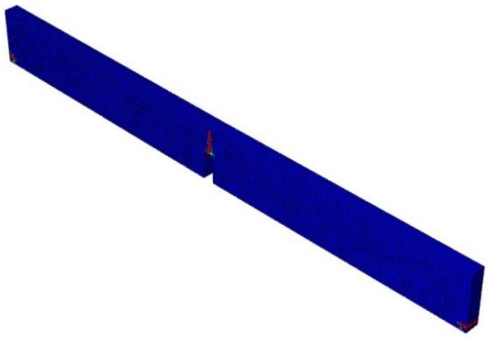
2.1 Tests on concrete

Crack initiation in concrete occurs due to micro cracking (due to shrinkage) and initial defects in concrete. Fracture in concrete can be broadly classified into two modes, Mode I and Mode II. Fig. 4(a) shows a solved finite element model in mode I (opening mode) crack propagation occurring due to direct or bending stresses acting on a concrete section with some initial defect. Fig. 4(b) shows a solved finite element model in mode II (sliding mode) crack propagation occurring due to shear. In both modes, plasticity effects are observed at the crack tip since stress concentration is high (Hillerborg *et al.* 1976). The stress around a crack tip (considering elastic effects only) is proportional to $\frac{1}{\sqrt{r}}$ as given by (Rybicki and Kanninen 1977).

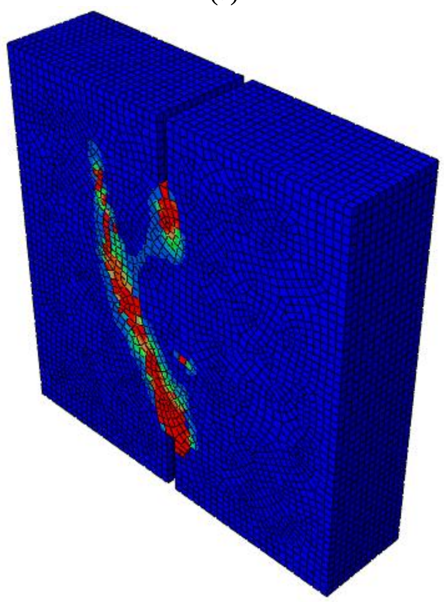
Stress intensity factor is the ratio of the stress at the crack tip to that of the nominal stress at any other section. Bazant (1984) introduced a correction factor to the stress intensity to account for size effects in concrete. The plasticization of concrete around the crack tip was modeled by Bazant and Kazemi (1990) using the cohesive crack model. Fracture toughness is the resistance offered by the material to crack extension and is estimated by conducting experiments as in Sih (1973) and Bazant and Oh (1983).Mode II crack propagation was tested and formulated by Reinhardt and Xu (2000).

2.2 Mechanics of the problem

The analytical model is derived using a free body



(a)



(b)

Fig. 4 (a) Crack propagation in mode I failure (b) Crack propagation in mode II failure

diagram of the separated wedge including the failure surface and the normal and shear stresses on them are considered (Kumar and Rao 2012). Considering equilibrium of the body in the vertical direction in Fig. 3, we achieve the expression for the load when the surface tractions are σ and τ as in Eq. (1) (Kumar and Rao 2012) where the variables have their usual meanings.

$$P = 2\pi(\tau - \sigma \tan\theta)\left(\frac{hd}{2} + \frac{(D_s - d)h}{4}\right) \tag{1}$$

When the load is at its maximum and slip occurs between the surfaces, the two bodies lose contact with each other. Hence the normal stress becomes zero. The equation now transforms to Eq. (2)

$$P_{ult} = 2\pi\, \tau_{max} \left(\frac{hd}{2} + \frac{(D_s - d)h}{4}\right) \tag{2}$$

2.3 Form of the stress-strain relationship (Natural aggregate concrete)

The following form of the compressive stress-strain relationships is achieved after numerous tests on sample of hardened concrete. This model had been proposed by Popvics (1973) and is still widely in many numerical simulations.

$$\frac{\sigma}{\sigma_0} = \left(\frac{\varepsilon}{\varepsilon_0}\right)\frac{n}{n - 1 + \left(\frac{\varepsilon}{\varepsilon_0}\right)^n} \tag{3}$$

$$n = 0.0004\sigma_0 + 1 \tag{4}$$

Eqs. (3) and (4) combined gives the complete form of the equation which is bound by the parameter (peak stress and strain at the peak stress). Eq. (5) has been derived in tension. The relationship mentioned here had been proposed by Wang and Tsu (2004).

$$\sigma = \begin{cases} E\varepsilon & ;\ \varepsilon < \varepsilon_0 \\ \sigma_0\left(\frac{\varepsilon_0}{\varepsilon}\right)^{0.4} & ;\ \varepsilon > \varepsilon_0 \end{cases} \tag{5}$$

2.4 Form of the stress-strain relationship (Recycled aggregate concrete)

The Technical Code of China (DG/TJ08-2018-2007) proposed an analytical model for the compressive stress-strain relationship (Xiao *et al*. 2011). The form of this relationship is given by Eq. (6)

$$\frac{\sigma}{\sigma_0} = \begin{cases} c_1\left(\frac{\varepsilon}{\varepsilon_0}\right) + (3 - 2c_1)\left(\frac{\varepsilon}{\varepsilon_0}\right)^2 + (c_1 - 2)\left(\frac{\varepsilon}{\varepsilon_0}\right)^3 & ;\ \varepsilon < \varepsilon_0 \\ \dfrac{\left(\frac{\varepsilon}{\varepsilon_0}\right)}{\left(\frac{\varepsilon}{\varepsilon_0}\right) + c_1\left(\frac{\varepsilon}{\varepsilon_0} - 1\right)^2} & ;\ \varepsilon > \varepsilon_0 \end{cases} \tag{6}$$

Similar for tension Eq. (7) holds

$$\frac{\sigma}{\sigma_0} = \begin{cases} g\left(\frac{\varepsilon}{\varepsilon_0}\right) - (g - 1)\left(\frac{\varepsilon}{\varepsilon_0}\right)^6 & ;\ \varepsilon < \varepsilon_0 \\ \left(\frac{\varepsilon_0}{\varepsilon}\right)^{g-1} & ;\ \varepsilon > \varepsilon_0 \end{cases} \tag{7}$$

The unknown constants are evaluated from regression of stress-strain curves till peak. Other methods of evaluation of stress-strain curves are as discussed in Gozalez *et al* (2012), Gonzalez *et al*. (2011), Bhikshma and Kishore (2010).

2.5 Physical properties of recycled aggregates

Until now, there are no special recycling technologies for producing RCA from waste concrete. The plants for production of natural crushed gravel aggregates, stone or rock are often used for RCA. The production process usually consists of primary, secondary crusher and screens. Various size fractions, for instance, 5-15, 15-31.5 mm and <5 mm can be usually produced. It should be noted that <5 mm fraction is normally not used for RAC (i.e., only the recycled coarse aggregate are used). It is found that the grading of RCA is usually within the limits for natural aggregates (Xiao *et al*. 2011).

RCA often contains a large amount of attached mortar and cement paste. The volume percentage of old mortar may range from 20% to 30% (Xiao *et al*. 2011), depending on the properties of the parent concrete and the production process. The attached mortar and cement paste on RCA are the principal cause of the difference between recycled coarse aggregate (RCA) and natural coarse aggregates. Test results indicated that RCA has the following technical properties (ACI 555R-01 (2001)). The bulk density of RCA is about 1290-1470 kg/m^3.The SSD density of RCA is about 2310-2620 kg/m^3 (Xiao *et al*. 2011). The absorptions of RCA are approximately 8.34% (10 min), 8.82% (30 min) and 9.25% (24 h) (Xiao *et al*. 2011), which is much larger than that of natural coarse aggregates and might be regarded as the most important characteristic. The porosity of RCA is approximately 23.3%, due to high mortar/ cement paste content. The crushing index of RCA is approximately 9.2% to 23.1%. The clay content of RCA is approximately 4.08%. In the technical code "Technical code for application of recycled concrete" (DG/TJ08-2018-2007), only RCA (minimum size over 5 mm) is permitted for producing RAC. The grading of the RCA must fall within the allowable limits for natural aggregate in JGJ 52-2006 "Standard for technical requirements and test method of sand and crushed stone or gravel". The RCA is classified into two types in terms of their SSD density, water absorption, and brick content. Considering the physical, chemical and physical-mechanical requirements, some limitations are also made for RCA (Xiao *et al*. 2011).

Due to the high water absorption characteristic of RCA, some adjustments have to be made for the mix design of RAC. Comprehensive experimental work was carried out. It is found that the mix design procedure for RAC in general does not differ much from that for conventional concrete. However, more water is required to attain a similar workability owing to the high water absorption of RCA. It is thus recommended by Xiao *et al*. (2011) to divide the water for RAC into two parts: the first part is determined according to the mix procedure for conventional concrete (with similar strength); the second part is determined according to the water absorption capacity (usually the 10 minute one) of the RCA, which is used to compensate the loss of slump of RAC. In practical mixing, the two parts of water are added together (Xiao *et al*. 2011).

2.6 Meso-level mechanics in recycled aggregate concrete

Recycled aggregates (RA) usually show particular characteristics as greater porosity and absorption, and lower density and strength than natural aggregates. In addition some studies on RAC indicate differences in the characteristics of the interfacial transition zones between the cement paste and the aggregates (ITZ).

The matrix-aggregate bond strength in RAC is higher or at least equal to the one developed with natural aggregates; this was verified by the author's previous experiences. On the contrary, some researches indicated that RAC had poor quality due to the higher water absorption, higher porosity and weaker ITZ (Folino and Xargay 2014); with the aim of improving the ITZ, the strength and the mechanical behavior of concrete they modified the mixing process. Chen *et al*. (2012) found that a concrete prepared with recycled aggregate derived from high-performance concrete developed higher compressive strength than a concrete prepared with recycled normal strength concrete aggregates; the first achieved the same strength level as a concrete prepared with natural crushed granite aggregates after 90 days of curing. This fact was attributed to the differences in both the strength of the coarse aggregates and the microstructural properties of the ITZ.

Recently, microstructural techniques have been applied to study the properties of recycled coarse aggregates. It was found that in some cases the recycling process can enhance their properties compared to natural sandstone coarse aggregates. Regarding the effect of RA on the mechanical properties of concrete, most of the previous researches confirm that the reduction in stiffness (i.e., elastic modulus) is higher than the reduction in strength; more recent studies show the same tendency (Cassucio *et al.* 2008). The mechanical properties of a high strength concrete made with recycled aggregate show that the properties of original concrete have significant influence on mechanical properties of RAC (Chen *et al*. 2012, Wengui *et al*. 2013).

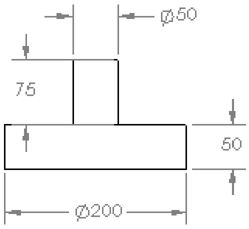
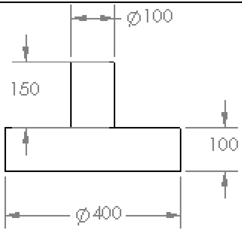
The parameters of fracture in RAC may be different due, mainly, to changes in the ITZ and the strength of the RA particles. As the bond strength increases and the aggregates are weaker the possibilities of crack propagation through the aggregates increases. The influence of matrix–coarse aggregate adherence on the fracture energy of normal and high strength concretes prepared with natural aggregates has been demonstrated. More recently, the effect of aggregate properties (modulus of elasticity, surface texture and size) on the weakness of ITZ and the failure process of concrete in compression were also discussed. Based on the cited/these studies, differences in the failure mechanism of concretes prepared with recycled and natural aggregates can be expected, especially when concrete strength increases (Chen *et al*. 2012).

The increase in bond strength and the reduction in stiffness that take place when natural coarse aggregate is replaced by recycled aggregate, increases the elastic compatibility between concrete phases (mortar and coarse aggregates) modifying the fracture process. This has a special interest in normal strength concrete. Compared with concrete including natural crushed stone as coarse aggregate, RAC has a lower stiffness, shows smaller reduction in tensile or compressive strengths and presents clear decrease in the energy of fracture and in the size of the fracture zone. A reduction in branching and meandering of cracks on the fracture surfaces was also observed. This fact is consistent with the increase in brittleness observed in concretes having aggregate with both improved interface strength and the elastic compatibility within mortar and coarse aggregate (Wengui *et al*. 2013).

There is adequate experimental research supporting the use of recycled aggregates. But the properties of recycled aggregates span a very wide spectrum. The physical and chemical properties depend heavily on the source and conditions prevailing to the parent structure. Therefore generalization of the properties of recycled aggregate concrete is very difficult. Moreover there exists very limited research on modeling of recycled aggregate concrete. This is important as extensive experimental research is difficult for every construction project which uses recycled aggregates. Therefore the field requires some very standard design methodology that can be used on a wide scale of projects.

This section discussed the underlying concept behind

Table 1 Table of nomenclature for specimens

Specimen	Nomenclature	Type of aggregate	Grade of concrete
	S1-NAC-25	Natural	M25
	S1-NAC-30	Natural	M30
	S1-RAC-25	Recycled	M25
	S1-RAC-30	Recycled	M30
	S2-NAC-25	Natural	M25
	S2-NAC-30	Natural	M30
	S2-RAC-25	Recycled	M25
	S2-RAC-30	Recycled	M30

the foundation of the present work. It discussed some basic fracture mechanics and its application in concrete undergoing different modes of failure. It also addressed issues about the finite element method, its implications and the structure of the problems that can be solved. Finally it highlighted aspects on the characterization of recycled aggregates to the meso-level and the mechanics associated to the failure of concrete at this level.

3. Experimental and numerical modeling

This scope of the section is to numerically determine the ultimate load carrying capacity of two self-similar flat-slab specimens and validate the results experimentally. It is also required to carry out the same exercise with recycled aggregate concrete (with full replacement) and compare the results. The material data required for the numerical simulations is collected from testing cubes (standard compressive strength), cylinders and prisms.

3.1 Experimental study

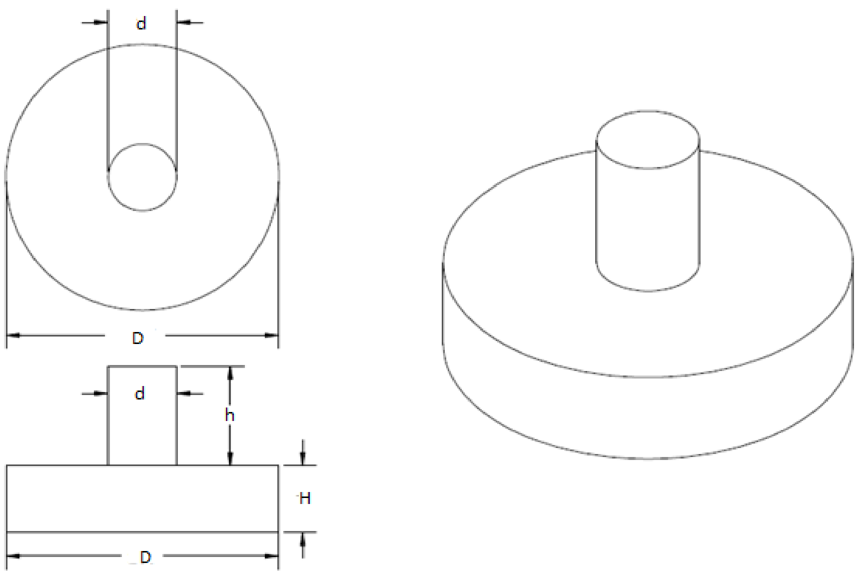
The present work is divided into three modules. Table 1 gives a three part nomenclature for all the samples and specimens used in the experimental investigations. The first part gives the size of the sample, second part gives the type of concrete used for casting and the third part gives the grade of concrete.

Experimental study involved the following steps.

• Preparation of three dimensional views and drawings of molds required for casting.
• Mix-design for M25 and M30 grades of concrete with natural aggregates.
• Casting a total of 15 samples per mix: For example, in the case M25 grade NAC, 3 cubes (150×150×150), 3 cylinders (diameter 150, height 300), 3 prisms (100×100 ×500), 3 S1 and 3 S2 were casted.
• Testing of cubes (compressive strength), cylinders (compressive strength and split tensile strength), prisms (4-point bending test) and flat-slab specimens
• Casting a total of 15 samples per mix as mentioned above but with recycled aggregates completely replacing the natural aggregates in concrete.
• Testing of cubes (compressive strength), cylinders (1 compressive strength, 2 compressive stress-strain characteristics), prisms (1 modulus of rupture, 2 tensile stress-strain characteristics) and flat-slab specimens (Mode-II shear).

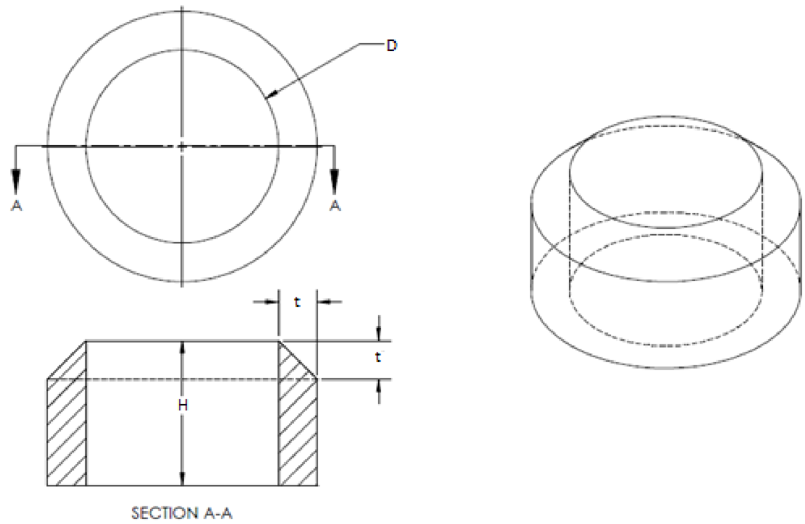
3.1.1 Preparation of molds for casting

The details of molds that were prepared in a workshop are mentioned below. The molds are prepared using



(a) (b)

Fig. 5 Specifications of the specimen; (a) For S1; *d*=50 mm, *D*=200 mm, *h*=75 mm, *H*=50 mm; (b) For S2; *d*=100 mm, *D*=400 mm, *h*=150 mm, *H*=50 mm



(a) (b)

Fig. 6 Circular support details; (a) For S1; *D*=100 mm, *H*=75 mm, *t*=20 mm; (b) For S2; *D*=200 mm, *H*=150 mm, *t*=20 mm

Table 2 Concrete mix used for casting

Constituents	M25	M30
Cement (kg/m^3)	383.2	450.0
Fine Aggregates (kg/m^3)	572.1	429.7
Coarse Aggregates (kg/m^3)	1161.5	1246.8
Water (kg/m^3)	191.6	185.4

different components so that they can be disassembled once the concrete is hardened (after 24 hours of casting). The specimens have a circular knife-edge support over which it is placed so that the punching failure can initiate. The failure occurs due to sliding of cracked surfaces against each other. These surfaces are inclined are the inclination depends on the diameter of the column and circular support. Fig. 5 shows the details of the concrete specimens to be tested in Mode II.

Fig. 6 shows circular supports that are required for the test specimens to fail in Mode II. These were made pretty strong so that it can take heavy loads without much deformation. As suggested in the figures, these were made out of 20 mm steel plates.

3.1.2 Mix-design (Natural aggregate concrete)

The design mix that was used for casting of cubes, cylinders, prisms and specimens are as mentioned below. Table 2 shows the concrete mix used for casting NAC. For RAC, the coarse aggregates used in NAC are completely replaced by recycled aggregates.

3.1.3 Test results (Natural aggregate concrete)

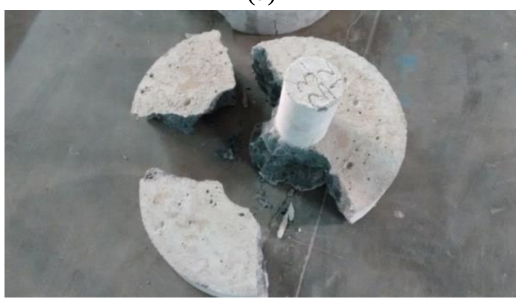
The test results for cubes, cylinders and prisms are mentioned below. These results were used to determine the stress-strain relationships to be used in numerical simulations of the model.

Table 3 shows the peak load values taken by each of the samples. It can be noted that the mixes are well in proportion as none of the samples have shown any extra-ordinary values. The test data for cylinders and prisms have been used in the numerical analysis. Fig. 7(a) and (b) show the test setup for a specimen.

Table 3 Test results for NAC

Test Sample	M25	M30
Cube (MPa)	25.2	32.8
Cylinder (MPa) (compression)	20.7	25.9
Cylinder (MPa) (split tensile)	1.7	1.8
Prism (MPa)	3.4	3.8
S1-NAC (kN)	25.9	33.6
S2-NAC (kN)	92.2	119.2

(a)

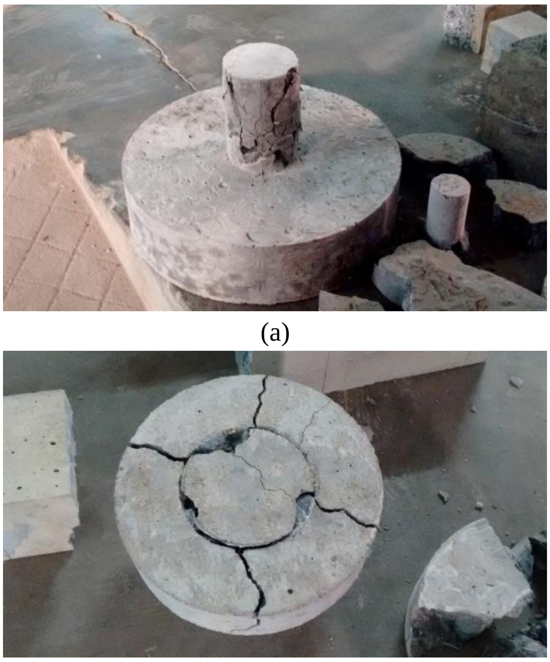


(b)

Fig. 7 (a) Test setup of S1-NAC-25; (b) Failure surface of S1-NAC-25

Table 4 Test results for RAC

Test Sample	M25	M30
Cube (MPa)	22.8	27.8
Cylinder (MPa) (compressive)	17.6	21.9
Prism (MPa)	2.5	2.6
S1-RAC (kN)	21.5	28.2
S2-RAC (kN)	79.3	97.4



(a)

(b)

Fig. 8 (a) A special kind of failure in case of RAC; (b) Failure of specimen casted with RAC

3.1.4 Mix-design (Recycled aggregate concrete)

The concrete mix used for recycled aggregate concrete is same as that used for natural aggregate concrete. The coarse aggregates from the previous mix had been completely replaced by recycled aggregates. All the other constituents are kept the same. However recycled aggregates have high water absorption capacity. Hence some corrections to water content are required to be made in order to provide sufficient free water for reactions to take place in the concrete.

3.1.5 Test results (Recycled aggregate concrete)

The test results for cubes, cylinders and prisms are mentioned below. Pre-peak behavior of recycled aggregate concrete in compression and tension had been achieved from lateral extensometer mounted cylinders and strain gauge (in the tensile zone) mounted prisms. Fig. 8(a) shows a special kind of failure noticed in case of recycled aggregate concrete. The ITZs are so weak that proper load transfer between the aggregate particles does not occur. Therefore the column fails way before any damage occurs in the slab. Fig. 8(b) shows a failed slab. The wedge separation can be clearly seen. Table 4 shows the peak loads taken by the specimens with RAC. It is noted that the cube strengths for both the mixes are lesser than that of NAC. This is as expected since it is known that RAC performs poorly because of multiple weak ITZs which fail prematurely.

3.2 Numerical study

The finite element procedures in this work have been adopted from Hutton (2004), Bathe (2007). The damaged plasticity material model and inelasticity have been taken from Simo and Hughes (1998). ABAQUS has been used as a finite element package for the analysis of the model (ABAQUS User's Manual 2012).

The numerical study involved the following steps.

• Collection of results from cylinder compression tests and 4-point bending tests on prism to implement equations 2.5, 2.6 and 2.7 to evaluate the complete stress-strain characteristics of normal aggregate concrete (compression and tension).

• Using these material properties to run finite element simulations on flat-slab models and evaluating the peak strength. This also includes observation of crack patterns and failure modes in the model.

• Collection of results from cylinder compression tests and 4-point bending tests on prism for recycled aggregate concrete. Calibration of data from these tests to fit in equations 2.8 and 2.9 which are standard forms of compression and tension.

• Using these material properties to run numerical simulations on models with recycled aggregate concrete and evaluating the peak strength.

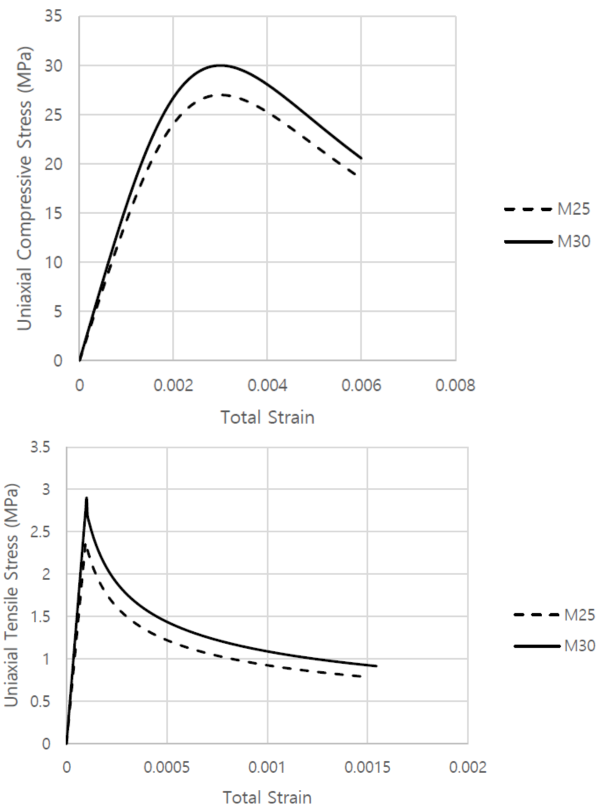
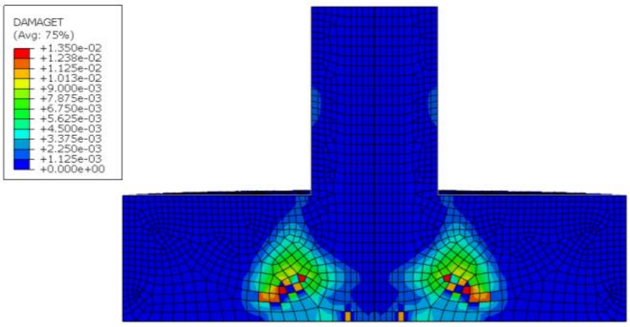


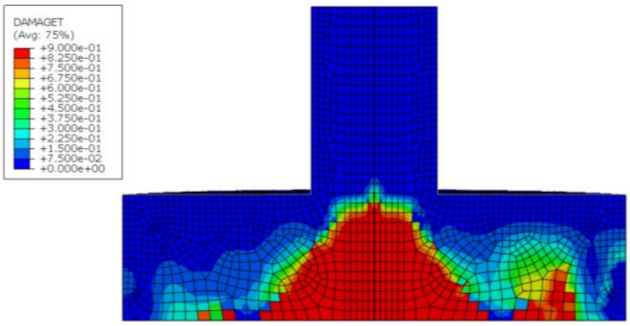
Fig. 9 (a) Compressive Stress-Strain (NAC); (b) Tensile Stress-Strain (NAC)

Table 5 Peak loads for M25 and M30

Test Sample	M25	M30
S1-NAC (kN)	22.4	33.6
S2-NAC (kN)	90.4	125.3



(a)



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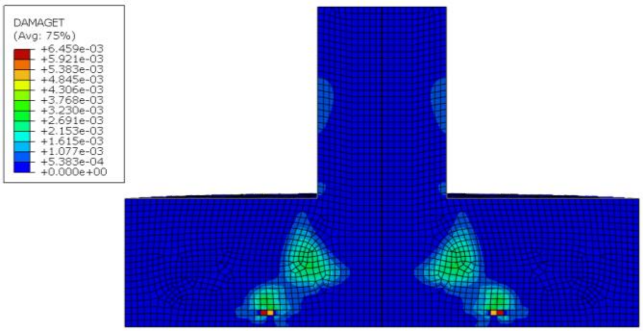

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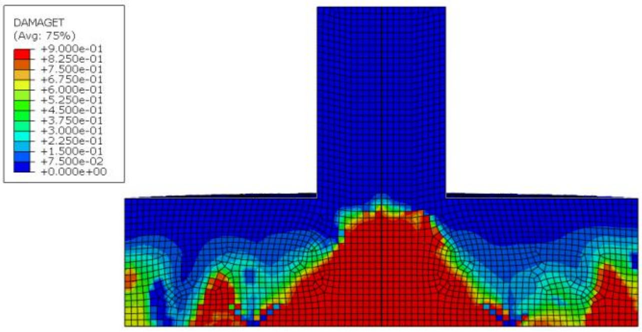


(d)

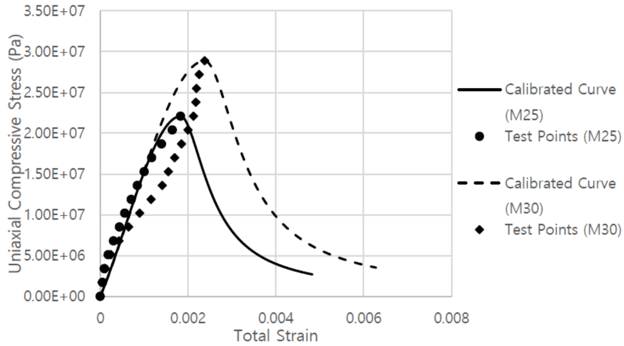
Fig. 10 Damage conditions at different frames (NAC)

3.2.1 Evaluating stress-strain relationships (Natural aggregate concrete)

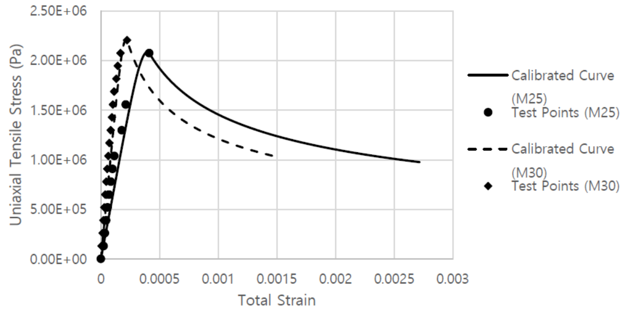
Concrete strength in compression and tension achieved from the experimental module has been used to generate the complete stress-strain characteristics in compression (Popovics 1973) and tension (Wang and Tsu 2004). The parameters used in these relations can be derived from the strength tests conducted on cylinders and prisms. Fig. 9(a) and 9(b) represent the behavior of NAC in compression and tension respectively.

Table 6 Peak loads for M25 and M30

Test Sample	M25	M30
S1-RAC (kN)	18.8	28.6
S2-RAC (kN)	79.1	107.1



(a)



(b)

Fig. 11 (a) Parameters for recycled aggregate concrete in compression; (b) Parameters for recycled aggregate concrete in tension

3.2.2 Finite element solution results (Natural aggregate concrete)

The finite element simulations are run on ABAQUS 6.11 (Abaqus User Manual). Concrete Damaged Plasticity Model has been used for evaluating damage occurring in the model. The specimens have been modeled using eight noded solid elements. The smaller specimen (S1) contained 8640 elements and the larger specimen (S2) contains 75480 elements. Damage has been considered to occur post the peak stress in both tension and compression. Damage parameters have been defined for strain levels post the peak stress. A stable time step of 3 μs has been used. The problem has been solved by applying a velocity quasi-statically on the top of the column. History outputs for the displacements of the top surface and reactions at the support were requested. Table 5 shows the ultimate load values for both the specimen.

Fig. 10 shows the damage occurring at initiation and just before collapse. (a), (b), (c) and (d) represent S1-NAC-25 damage initiation, S1-NAC-25 collapse, S2-NAC-25

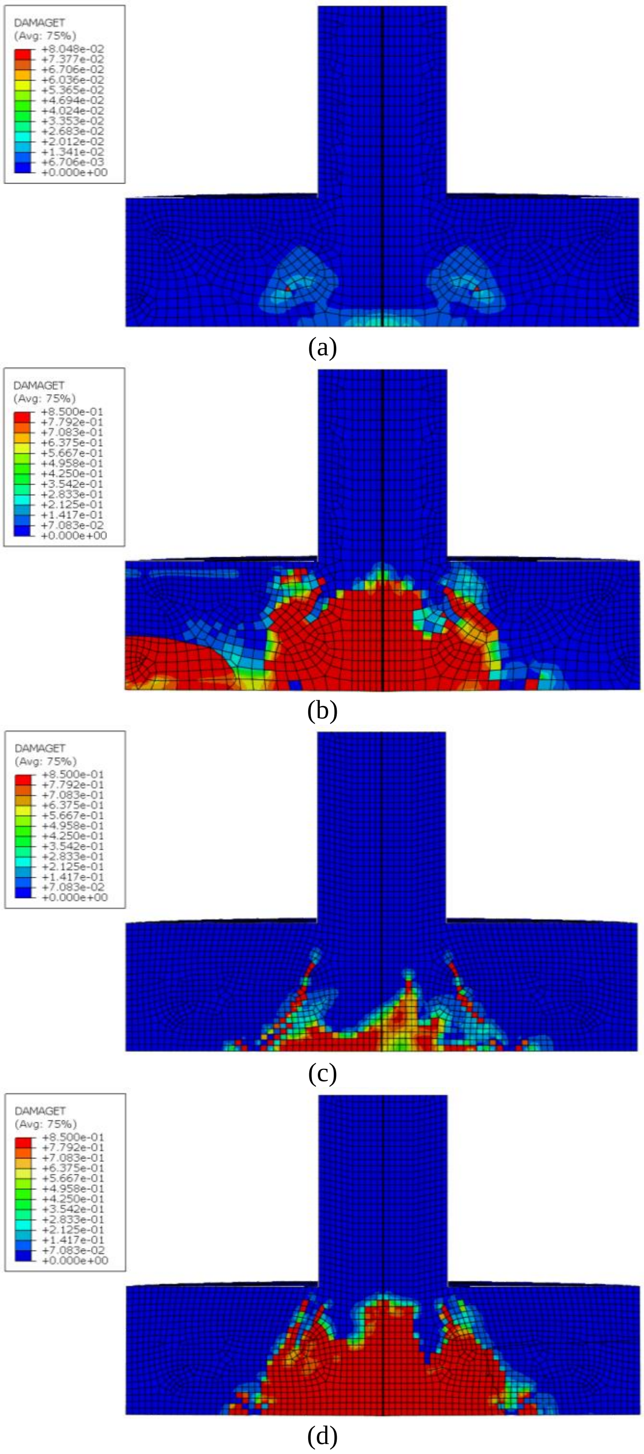


Fig. 12 Damage conditions at different frames (RAC)

damage initiation and S2-NAC-25 collapse respectively. The red portions denote maximum damage. The figures clearly suggest that even after wedge separation the failure mode changes from Mode II to Mode I.

3.2.3 Finite element solution results (Recycled aggregate concrete)

The material properties for recycled aggregate concrete have been achieved from testing cylinders and prisms. Since stress-strain characteristics were available till the peak stress, the post peak behavior was found out by calibrating these tested values with standard stress-strain curves for recycled aggregate concrete. Fig. 11(a) and 11(b) show the tested data along with the calibrated standard curves. These curves have been arrived at by regression of the known data points in the form of the Eqs. (6) and (7) for compression and tension respectively. The data for these curves have been arrived at by testing cylinders and prism with extensometers and strain gauges respectively in UTMs.

Table 6 shows the ultimate load values for both the specimen casted with RAC. It is observed that the peak values are smaller than that with NAC.

Fig. 12 shows the damage occurring at initiation and just before collapse. (a), (b), (c) and (d) represent S1-RAC-30 damage initiation, S1-RAC-30 collapse, S2-RAC-30 damage initiation and S2-RAC-30 collapse respectively. The red portions denote maximum damage. More smeared cracks are observed and the damage is not confined as was in the case of NAC. The collapse is more catastrophic and sudden in case of RAC.

4. Comparison study

4.1 Comparison of experimental and numerical results

Table 7 shows the comparison of load carrying capacity from experimental and numerical results. The minute discrepancies are due to the fact that load transfer from the test setup to the sample is not perfect. The deformations of the testing equipment are not considered. However a very detailed model can accurately predict the load bearing capacity of the slab specimens.

4.1.1 Behavior of natural and recycled aggregate concrete

Table 8 shows the comparison of load capacity of flat-

Table 7 Comparison between experimental and numerical results (All in kN)

Specimen	Experimental	Numerical
S1-NAC-25	25.9	22.4
S2-NAC-25	92.2	90.4
S1-NAC-30	33.6	33.6
S2-NAC-30	119.2	125.3
S1-RAC-25	21.5	18.8
S2-RAC-25	79.3	79.1
S1-RAC-30	28.2	28.6
S2-RAC-30	97.4	107.1

Table 8 Comparison of natural and recycled aggregate concrete (All in kN)

Specimen	Natural Aggregate (NAC)	Recycled Aggregate (RAC)
S1-25	24.2	20.2
S2-25	91.3	79.2
S1-30	32.1	28.4
S2-30	122.3	102.3

Table 9 Comparison of natural and recycled aggregate concrete (All in MPa)

Specimen	Natural Aggregate (NAC)	Recycled Aggregate (RAC)
S1-25	2.055	1.715
S2-25	1.938	1.683
S1-30	2.725	2.411
S2-30	2.596	2.171

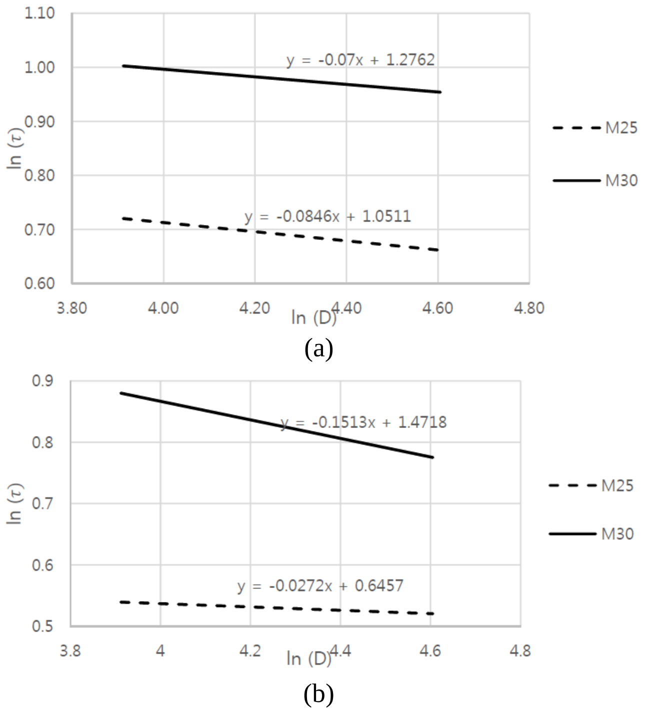


Fig. 13 (a) Size-effect for natural aggregate concrete; (b) Size-effect for recycled aggregate concrete

slabs with natural aggregate concrete and recycled aggregate concrete.

4.1.2 Shear stress variation in natural and recycled aggregate concrete

Table 9 shows the variation of shear stress in flat-slabs with natural aggregate concrete and recycled aggregate concrete.

4.1.3 Size-Effect on shear strength of concrete

The figures below show the size effect on shear strength of concrete. Fig. 13(a) shows the size effect of shear stress on the inclined wedge for NAC.

$$\tau = 1.2762D^{-0.07} \tag{8}$$

$$\tau = 1.0511D^{-0.0846} \tag{9}$$

Eqs. (8) and (9) give the variation of shear stress with the depth of the slab for NAC. It is noticed that the variation of shear with the size of the model does not vary much by varying the grade of concrete for NAC.

Fig. 13(b) shows the size effect of shear stress on the inclined wedge for RAC.

$$\tau = 1.4718D^{-0.1513} \tag{10}$$

$$\tau = 0.6457D^{-0.0272} \tag{11}$$

Eqs. (10) and (11) give the variation of shear stress with the depth of the slab for RAC. The variation with the grade of concrete is very much observable in case of RAC. This can be attributed to the fact that the probability that structural flaws in RAC is much higher in comparison to NAC. This is again because of weak ITZs present in the aggregate-concrete matrix.

This section described all results obtained in due course of the work. The outcome is that the use of recycled aggregate concrete almost eliminates the cost of coarse aggregates, therefore reducing the material cost. Although there is a drop in the concrete strength and the behavior is more brittle, the cost to benefit ratio is as good as natural aggregate concrete. The failure in most cases is sudden and catastrophic. It was not noted that even when it was tried that the damage is confined in a certain region of the specimen, however in most cases cracks developed well outside this zone of confinement. However these factors cannot entirely rule out the use of recycled aggregates in construction. The design philosophy would now require higher and number of other safety factors resulting in bigger cross–sections of structural members. Even then construction costs will not shoot up since the material involved is very cheap if produced on a mass scale.

5. General discussion

- The work has been well defined right from the beginning. The specimens were not very standard, so molds were required to be fabricated. They were prepared with utmost care so that there are no eccentricities between column and slab and slab and support. All detailed drawings of the molds were prepared with very accurate dimensions ensuring comparable results in numerical simulations.
- In the mix-design it was found that M30 contains higher percentage of cement and coarse aggregates. This is the reason behind the increase in strength of M30 concrete. It was also found that this grade of concrete is more ductile in nature and has higher fracture energy in the tensile region.
- In the numerical simulations, it has been ensured that the load is being applied quasi–statically. This is verified from the time history of the kinetic energy and the strain energy stored in the model. Mesh convergence for one of the models has been verified and to ensure converged results for the rest of the models, the mesh size is unaltered even when for the bigger specimen. Each analysis has taken around 48 hours to run on an i3 processor when run parallel in 2 cores.
- The material properties for natural aggregate concrete are derived from standard curves. The parameters required are the compressive strength, tensile strength, Young’s modulus and Poisson’s ratio. However for the recycled aggregate concrete, standard curves are difficult to obtain. The reason is that the strength offered by recycled aggregates is dominated by the source. Thus material properties are to be evaluated by experiments.

The test data obtained is calibrated with the standard forms of the compressive and tensile behavior. These calibration constants are evaluated by nonlinear regression.

• The results show that recycled aggregate concrete is poor in load carrying capacity as compared to natural aggregate concrete. The main reason behind this is that there always exists a region known as the Interfacial Transition Zone (ITZ) around aggregates in concrete. Since these aggregates have been recycled, there exist two ITZs which in turn reduced the bond strength between aggregates and mortar. Recycled aggregates also have a high water absorption capacity. Thus there is very little free water available. If this property is sustained then the bond between aggregates and mortar does not get enough strength even after proper curing.

• The size effect in recycled aggregate concrete has also been evaluated. It has been found out that the variation of size effect with the characteristic strength of concrete is more dominant in recycled aggregate than that in normal aggregate concrete. The reason behind this is that failure in recycled aggregate concrete is always in mixed mode, because of the formation of multiple ITZs, however simple the loading is. Therefore as size increases the probabilistic size effect is more dominant than deterministic size effect.

• This model can be extended by applying reinforcement against shear failure and by using fiber to the concrete. The effect of these parameters can be evaluated for Mode II failure in recycled aggregate concrete and comparing the results with natural aggregate concrete. The variation of shear characteristics on varying the angle of the separated wedge can also be analyzed. This can provide a tradeoff between failure due to bending and due to shear. On a more advanced level the concrete modeling can be done at the meso-level and more detailed failure regions can be identified. However this sort of an analysis would require high proficiency in finite element method and huge computational efficiency.

6. Conclusions

A lot of literature is available on the shear behavior of concrete. Researchers have worked on Mode II failure in concrete using various specimens and different modeling techniques. This paper dealt with the effect the Mode II failure in recycled aggregate concrete. Although the load carrying capacity of recycled aggregate concrete is not as good as natural aggregate concrete, but it still bears similar characteristics in the concrete matrix. The load carrying capacity of a very realistic model has been compared by varying the mix and type of aggregate. This model is often used in foundations and as flat-slabs for relatively small buildings. A size effect analysis has also been done in order to evaluate the effect of both natural and recycled aggregate concrete on the size of the specimen. The results obtained are very realistic and do not involve much of statistical analysis.

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