Influence of Concrete Strength on the Stress-Strain Behavior of Spirally Confined Recycled Aggregate Concrete

Muhammad J Munir*, Syed M S Kazmi, Yufei Wu, and Indubushan Patnaikuni
School of Engineering, RMIT University, 376-392 Swanston St, Melbourne, Victoria-3001, Australia.

* s3636560@student.rmit.edu.au

Abstract. Costly and non-environment-friendly methods are used to improve the inferior behavior of recycled aggregate concrete (RAC). Conversely, the strength enrichment of concrete due to confinement provided by lateral reinforcement is ignored in the design of concrete compression members. The focus of this study is to investigate the role of pre-existing transverse reinforcement and different design strengths of concrete on the stress strain behavior of RAC. For this reason, stress-strain behavior of spiral steel confined concrete specimens having variable confinement pressure, recycled aggregates (RA) replacement percentage and design strength is investigated. The results show a drop in compressive strength of concrete with the increase in replacement percentage of RA. However, steel confinement has a positive role to counterbalance the adverse effect of RA replacement on concrete strength. Improved ductility and stress-strain behavior of RAC are observed with the increase in confinement pressure. Based on the results, the un-utilized pre-existing steel spiral reinforcement in the concrete compression members can offset the inferior performance of RAC resulting into sustainable and cost-effective construction.

1. Introduction
Demolishing of the older buildings and construction of new structures cause a huge quantity of construction and demolition (C&D) waste generation each year around the globe. For instance, China produces 0.2 billion tons of C&D waste yearly [1]. Similarly, Australia dumps roughly 5 million tons of waste concrete to landfills [2]. Concrete as a most widely used construction material worldwide is mainly composed of natural resources. Natural aggregates (NA) occupy nearly 50% of the total volume of concrete [3]. Recycling of C&D waste in the concrete as recycled aggregates (RA) to manufacture recycled aggregate concrete (RAC) can serve two functions i.e. natural resource conservation and saving of land fill spaces.

A lot of researchers have studied the utilization of different kinds of wastes in the novel construction materials to achieve sustainability in construction [4-7]. For instance, mechanical and durability performance of RAC has been studied to investigate the feasibility of recycling C&D waste in the form of RA [8-14]. Old adhered mortar attached on the surface of RA is the major difference between NA and RA resulting into the inferior performance of RAC as compared to the traditional concrete [3, 15, 16]. Inferior performance of RAC is the reason behind lower practical application of RAC (i.e. non-structural purposes only such as road bases). About, 20 and 40% reduction in the compressive strength and modulus of elasticity was stated for 100% RA replacement in RAC as compared to normal aggregate concrete (NAC) [17, 18]. Therefore, the performance of RAC deteriorates with the increase amount of RA replacement, which is the major worry regarding the utilization of RA in the structural
concrete. Numerous investigators have explored variety of methods to improve the performance of RAC [6, 19, 20]. Lateral confinement using the materials like fiber-reinforced polymers (FRP) and steel tubes improves the compressive strength and other mechanical properties of NAC [21-23]. Similarly, performance of RAC can also be improved using confinement methods [24]. For example, Yang and Han [25] used steel tubes to confine RAC resulting into the improvement in the strength and deformation capacity. Compressive strength, ductility and stress strain behavior of NAC can also be improved by providing confinement using spiral steel reinforcement [26]. Limited work is available in the open literature regarding the role of lateral steel spirals in the enhancement of mechanical and stress strain performance of RAC. Lateral confinement in the form of steel spirals is commonly provided in the design of concrete columns. Contribution of these lateral steel spirals in the enhancement of compressive behavior of concrete columns is generally ignored in the current design method of compression members. It is therefore important to study the ability of un-used spiral steel reinforcement to offset the inferior performance of RAC. Steel spirals are already present in the concrete compression members. Therefore, performance enhancement of RAC through pre-existing confinement by steel spirals may be an economical, sustainable and easy to adopt solution for the structural application of RAC. The focus of this study is to investigate the role of pre-existing transverse reinforcement and different design strengths of concrete on the stress strain behavior of RAC. For this reason, stress-strain behavior of spiral steel confined concrete specimens having variable confinement pressure, recycled aggregates (RA) replacement percentage and design strength is investigated.

2. Materials and methods
RA and crushed granite NA having size 4 – 20 mm were used in this study. Figure 1 shows the size distribution curves for NA and RA fulfilling the limits of ASTM C33:2016 [27]. Table 1 shows the higher water absorption and lower bulk density of RA as compared to NA, which may be related to the presence of old adhered mortar with the surface of RA [28, 29]. Ordinary Portland cement (type P.II52.5R), river sand and tap water were used to manufacture all the mixes shown in table 2. Before concrete mixing, all the aggregates were first oven-dried at 105oC for 24 hours and then additional water was added in each mixture to consider the water absorption capacity of aggregates. Slump value between 90-100 mm was observed for series A and B. Similarly, 50-60 mm slump was noted for the concrete mixes belonging to series C.

![Figure 1. Gradation of NA and RA.](image-url)
Table 1. Physical characteristics of NA and RA.

| Property of aggregates                  | NA   | RA   |
|-----------------------------------------|------|------|
| Water absorption (%)                    | 1.30 | 6.85 |
| Apparent specific gravity               | 2.66 | 2.55 |
| Density (kg/m³)                         | 1513 | 1414 |
| Crushing value (%)                      | 27.0 | 31.0 |

To confine the concrete specimens, 3 mm round steel wire having yield and ultimate strength of 730 and 861 MPa, respectively was used as a spiral reinforcement. Elastic modulus and ultimate strain of steel wire were 200 GPa and 7.72%, respectively. For each series in table 2, forty-eight (i.e., 12 unconfined and 36 steel spiral confined) concrete specimens of size 150 x 300 mm were cast in accordance with ASTM C192:2016 [30] and 28 days curing was performed. Test variables included confinement pressures, replacement ratios of RA and target strengths of NAC specimens. Four different replacement ratios of RA (i.e., 0, 20, 50 and 100%) along with three different target strengths of NAC specimens (i.e., 25 MPa, 40 MPa and 60 MPa) were considered during the study. To consider varying confinement levels, three different pitches (i.e., center to center spacings) of steel spirals (i.e., 40, 30 and 20 mm, respectively) were selected considering Wu and Wei [31] model. To examine the pure effect of confinement pressure, no longitudinal reinforcement and concrete cover were considered in this study.

Table 2. Details of concrete mix design.

| Series | RA replacement ratio (%) | Cement | Sand   | NA   | RA  | Water | Extra water | Admixture (ml/m³) |
|--------|--------------------------|--------|--------|------|-----|-------|-------------|-------------------|
| A      | 0                        | 201.6  | 462.5  | 865.1| --- | 100.8 | 11.2        | ---               |
|        | 20                       | 201.6  | 462.5  | 691.5| 161.6| 100.8 | 19.9        | ---               |
|        | 50                       | 201.6  | 462.5  | 432.2| 404.0| 100.8 | 33.0        | ---               |
|        | 100                      | 201.6  | 462.5  | ---  | 807.9| 100.8 | 55.3        | ---               |
| B      | 0                        | 288.0  | 528.8  | 710.1| ---  | 135.3 | 9.2         | ---               |
|        | 20                       | 288.0  | 528.8  | 568.1| 132.7| 135.3 | 16.4        | ---               |
|        | 50                       | 288.0  | 528.8  | 350.0| 331.8| 135.3 | 27.3        | ---               |
|        | 100                      | 288.0  | 528.8  | ---  | 663.7| 135.3 | 45.4        | ---               |
| C      | 0                        | 313.6  | 539.8  | 672.4| ---  | 78.4  | 8.7         | 967.8             |
|        | 20                       | 313.6  | 539.8  | 537.9| 125.6| 78.4  | 15.6        | 966.7             |
|        | 50                       | 313.6  | 539.8  | 336.2| 314.2| 78.4  | 25.9        | 964.9             |
|        | 100                      | 313.6  | 539.8  | ---  | 628.4| 78.4  | 43.0        | 962.0             |

For each mix combination, three specimens were cast, cured and tested. The labels of concrete cylinders display RA replacement percentage (R0, R20, R50 and R100 specify 0, 20, 50 and 100% RA replacement, respectively), pitches of steel spirals (S20, S30 and S40 mean pitch of 20, 30 and 40 mm, respectively) and design strengths of NAC (series A, B and C show the mix design with target strength of 25 MPa, 40 MPa and 60 MPa for NAC, respectively). For instance, R20-S40-B denotes the concrete mix with 20% of RA replaced with NA, 40 mm pitch of steel spirals and having the design strength of 40 MPa for NAC. Compression tests were performed on the specimens using displacement control mode with a rate of 0.3 mm/min. Data acquisition system and four linear variable displacement transducers (LVDTs) mounted at 90° relative to each other were used to record the load and to measure the axial deformation, respectively. During the compression test, applied load and deformation were measured to examine the stress strain behavior of all the concrete specimens.

3. Results and discussions
3.1 Axial stress strain performance

Figure 2 depicts the effect of RA replacement on the stress strain behavior of all the confined and unconfined specimens. The axial strain of all the concrete specimens was calculated by the average value from the four LVDTs mounted vertically around the specimen. Shape of the stress-strain curves for all the confined and unconfined specimens changes steadily and flatten with the increase in RA replacement ratio. Reduction in the elastic modulus (i.e. initial slope) and a lower peak load are observed for the un-confined concrete specimens with the rise in RA replacement ratio as shown in figures 2(a-c). For series-A, un-confined concrete specimens display a reduction in the slope of descending branches of stress strain curves with the rise in replacement ratio of RA. This may be attributed to the inferior strength of concrete in series-A with the increase in RA replacement ratio. For the series B and C, the descending portions of the stress-strain curves are observed steeper with the rise in RA replacement ratio, which may be attributed to the more brittle behavior of RAC in comparison with NAC as reported in a past studies [32, 33]. Un-confined concrete specimens also show reduced energy absorption capacity because of the smaller area under the curve with the rise in RA replacement ratio.

For all the confined specimens, lower stress-strain curves are obtained with the rise in RA replacement ratio, as shown in figures 2(d-l). Effect of confinement in terms of strength improvement increases with the rise in the replacement ratio of RA. Furthermore, the effect of confinement is observed more prominent for lower strength concrete such as series-A concrete specimens as compared to series B and C specimens. Similar findings are reported in the previous study by Wang et al. [34]. Reduction in the compressive strength due to the increase in RA replacement ratio is also observed in the presence of lateral confinement, which is consistent with the observations of Teng et al. [35] for FRP confined RAC.
Figure 2. Effect of RA replacement ratio on the stress-strain behaviour of (a) unconfined specimens – Series-A, (b) unconfined specimens – Series-B, (c) unconfined specimens – Series-C, (d) confined S40 specimens – Series-A, (e) confined S40 specimens – Series-B, (f) confined S40 specimens – Series-C, (g) confined S30 specimens – Series-B, (h) confined S30 specimens – Series-C, (i) confined S30 specimens – Series-D, (j) confined S30 specimens – Series-E, (k) confined S30 specimens – Series-F, (l) confined S30 specimens – Series-G.
3.2 Compressive strength

Table 3 shows the effect of strength, RA replacement ratio and confinement pressure on the average compressive strength values of all the confined and un-confined concrete specimens. For all the specimens, the drop in compressive strength is observed with the increase in RA content. For instance, R100-A, R100-B and R100-C specimens show 43, 37 and 33% decline in the average compressive strength as compared to R0-A, R0-B and R0-C specimens, respectively. The difference in strength drop is linked to the difference in concrete mix design for each series. Similar trend was also reported by Pacheco et al. [36]. The increase in the confinement pressure results into the increase in the average compressive strength of the confined concrete specimens. All the confined concrete specimens of series-A except R100-S40-A show average compressive strength higher as compared to un-confined R0-A specimens. Similarly, all the confined concrete specimens of series-B except R50-S40-B, R100-S40-B and R100-S30-B display average strength higher as compared to the un-confined R0-B specimens. For series-C, the compressive strength values of R0-S40-C, R0-S30-C, R0-S20-C and R20-S20-C specimens are observed higher as compared to un-confined R0-C specimens, whereas, all the other specimens show compressive strength still lower than un-confined R0-C specimens. By comparing, R100-S40-B with R0-S40-B and R100-S20-B with R0-S20-B, drop in strength due to the use of RA reduces to 36% and 32% after providing the confinement with 40 mm and 20 mm pitch of spiral reinforcement, respectively. Similar behavior is observed for series A and C concrete specimens, which shows the positive role of confinement pressure to counter the adverse effects of RA replacement. Similar trend was also observed by Zhao et al. [37] for the FRP confined RAC specimens.

Table 3. Mechanical properties of all the specimens.

| Specimen | Series A (25 MPa) | Series B (40 MPa) | Series C (60 MPa) |
|----------|------------------|------------------|------------------|
|          | Compressive strength | Modulus of elasticity | Compressive strength | Modulus of elasticity | Compressive strength | Modulus of elasticity |
| R0       | 26.26             | 25.30             | 40.10             | 33.76             | 61.82             | 46.93             |
| R20      | 25.46             | 19.89             | 37.95             | 29.08             | 54.36             | 37.25             |
| R50      | 21.78             | 19.72             | 29.55             | 24.52             | 45.45             | 32.99             |
| R100     | 15.09             | 12.82             | 25.31             | 20.30             | 41.30             | 27.67             |
| R0-S40   | 36.05             | 25.78             | 48.63             | 33.16             | 63.88             | 46.55             |
| R20-S40  | 34.66             | 19.85             | 42.48             | 25.68             | 56.70             | 37.96             |
| R50-S40  | 28.88             | 16.93             | 34.56             | 21.09             | 48.31             | 32.59             |
| R100-S40 | 22.75             | 12.72             | 31.34             | 18.71             | 43.07             | 27.09             |
| R0-S30   | 41.56             | 22.99             | 53.05             | 31.16             | 65.22             | 46.18             |
| R20-S30  | 41.41             | 18.71             | 47.37             | 27.13             | 61.72             | 38.05             |
| R50-S30  | 34.37             | 16.68             | 40.05             | 21.95             | 52.50             | 33.39             |
| R100-S30 | 32.51             | 12.08             | 34.36             | 18.50             | 44.22             | 27.77             |
| R0-S20   | 51.63             | 19.32             | 59.67             | 28.69             | 71.95             | 42.79             |
| R20-S20  | 48.33             | 18.09             | 51.22             | 24.28             | 64.99             | 35.61             |
| R50-S20  | 42.82             | 16.70             | 44.09             | 19.39             | 57.09             | 31.86             |
| R100-S20 | 39.25             | 11.91             | 40.78             | 16.62             | 50.22             | 26.95             |

3.3 Modulus of elasticity

Table 3 depicts the effect of design strength, RA replacement ratio and confinement pressure on the average elastic modulus of all the confined and un-confined concrete specimens. Modulus of elasticity of all the specimens was calculated using the initial slope of the axial stress-strain curve following the method used by Carneiro, Lima, Leite and Toledo Filho [38]. For all the specimens, the drop in the modulus of elastic is noticed with the increase in RA replacement ratio. For instance, R100-A, R100-B and R100-C specimens display 49, 40 and 41% decline in average modulus of elasticity as compared to R0-A, R0-B and R0-C specimens, respectively. The drop in modulus of elasticity of concrete specimens may be linked to the inferior modulus of elasticity of RA (owing to porous old attached mortar), whereas, the difference in the reduction of modulus of elasticity for each series is related to the difference in the concrete mix design. Similar trend of modulus of
elasticiy was also reported in the previous studies [39, 40]. The increase in confinement pressure results in a drop in average modulus of elasticity. For instance, R20-A specimens show modulus of elasticity of 19.9 GPa, which reduces to 19.8, 18.7 and 18.1 GPa for R20-S40-A, R20-S30-A and R20-S20-A specimens, respectively. Similarly, R100-B specimens show modulus of elasticity of 20.3 GPa, which decreases to 18.7, 18.5 and 16.6 GPa for R100-S40-B, R100-S30-B and R100-S20-B specimens, respectively. In past studies, researchers [41, 42] also reported the reduction in modulus of elasticity of NAC with the increase in confinement pressure. The drop in the modulus of elasticity of concrete is attributed to the presence of lateral steel spirals, which form gaps between the surrounding concrete and steel spirals owing to the shrinkage of concrete [43]. Reduction of the cross-sectional area of concrete at the location of steel spirals due to the concrete shrinkage may result in decrease in the effective concrete area leading towards drop in the modulus of elasticity of confined specimens.

4. Summary and conclusions

Costly and non-environment-friendly methods are used to improve the inferior behavior of recycled aggregate concrete (RAC). Conversely, the strength enrichment of concrete due to confinement provided by lateral reinforcement is ignored in the design of concrete compression members. The focus of this study is to investigate the role of pre-existing transverse reinforcement and different design strengths of concrete on the stress-strain behavior of RAC. For this reason, stress-strain behavior of spiral steel confined concrete specimens having variable confinement pressure, recycled aggregates (RA) replacement percentage and design strength is investigated. Based on results obtained during this study, following conclusions may be drawn.

- Steel spirals are already present in the concrete compression members. Therefore, performance enhancement of RAC through pre-existing confinement by steel spirals may be an economical, sustainable and easy to adopt solution for the structural application of RAC.
- Shape of the stress-strain curves for all the confined and un-confined specimens changes steadily and flatten with the increase in RA replacement ratio. However, improved stress-strain behavior is observed in the confined concrete specimens.
- Effect of confinement in terms of strength improvement increases with the rise in the replacement ratio of RA. The effect of confinement is also observed more prominent for lower strength concrete such as series-A concrete specimens as compared to series B and C specimens.
- Confinement through spiral steel reinforcement can offset the inferior performance of RAC. For example, all the spiral steel confined concrete specimens of series A except R100-S40-A show average compressive strength higher in comparison with unconfined R0-A specimens.
- Modulus of elasticity for all the specimens reduces with the increase in the amount of RA. Moreover, decline in the modulus of elasticity of spiral steel confined specimens is also observed which may be related to the decrease in the effective concrete area due to the shrinkage of concrete at the location of the spiral.
- Based on the results, the pre-existing steel spiral reinforcement in the concrete compression members can offset the inferior performance of RAC resulting into sustainable and cost-effective construction.

5. References

[1] Xiao J, Li W and Poon C 2012 Recent studies on mechanical properties of recycled aggregate concrete in China—A review Sci China Tech Sci. 55 1463-80
[2] Tam V W Y 2009 Comparing the implementation of concrete recycling in the Australian and Japanese construction industries J. Clean Prod. 17 688-702
[3] Shi C, Li Y, Zhang J, Li W, Chong L and Xie Z 2016 Performance enhancement of recycled concrete aggregate – A review J. Clean Prod. 112 466-72
[4] Kazmi S M S, Abbas S, Saleem M A, Munir M J and Khitab A 2016 Manufacturing of sustainable clay bricks: Utilization of waste sugarcane bagasse and rice husk ashes Const Build Mat. 120 29-41
[5] Kazmi S M S, Munir M J, Abbas S, Saleem M A, Khitab A, Rizwan M 2017 Development of lighter and eco-friendly burnt clay bricks incorporating sugarcane bagasse ash Pak J Eng & App Sci. 21 1-5
[6] Kazmi S M S, Munir M J, Wu Y-F and Patnaikuni I 2018 Effect of macro-synthetic fibers on the fracture energy and mechanical behavior of recycled aggregate concrete Const Build Mat. 189 857-68
[7] Munir M J, Kazmi S M S and Wu Y-F 2017 Efficiency of waste marble powder in controlling alkali-silica reaction of concrete: A sustainable approach Const Build Mat. 154 590-9
[8] Xuan D, Zhan B and Poon C S 2017 Durability of recycled aggregate concrete prepared with carbonated recycled concrete aggregates Cem Con Comp. 84 214-21
[9] Oikonomou N D 2005 Recycled concrete aggregates Cem Con Comp. 27 315-8
[10] Kazmi S Minhaj S, Abbas S, Munir M J and Khitab A 2016 Exploratory study on the effect of waste rice husk and sugarcane bagasse ashes in burnt clay bricks J Build Eng. 7 372-8
[11] Abbas S, Saleem M A, Kazmi S M S and Munir M J 2017 Production of sustainable clay bricks using waste fly ash: Mechanical and durability properties J Build Eng. 14 7-14
[12] Kazmi S M S, Abbas S, Nehdi M L, Saleem M A and Munir M J 2017 Feasibility of using waste glass sludge in production of ecofriendly clay bricks J Mat Civil Eng. 29
[13] Kazmi S M S, Munir M J, Wu Y-F, Hanif A and Patnaikuni I 2018 Thermal performance evaluation of eco-friendly bricks incorporating waste glass sludge J Clean Prod. 172 1867-80
[14] Kazmi S M S, Munir M J, Patnaikuni I, Wu Y-F and Fawad U 2018 Thermal performance enhancement of eco-friendly bricks incorporating agro-wastes Energ Buildings 158 1117-29
[15] Sáez del Bosque I F, Zhu W, Howind T, Matias A, Sánchez de Rojas M I and Medina C 2017 Properties of interfacial transition zones (ITZs) in concrete containing recycled mixed aggregate Cem Con Comp. 81 25-34
[16] de Brito J, Ferreira J, Pacheco J, Soares D and Guerreiro M 2016 Structural, mechanical and durability properties and behaviour of recycled aggregates concrete J Build Eng. 6 1-16
[17] Xiao J, Li W, Fan Y and Huang X 2012 An overview of study on recycled aggregate concrete in China (1996–2011) Const Build Mat. 31 364-83
[18] Kou S C, Poon C S and Chan D 2007 Influence of fly ash as cement replacement on the properties of recycled aggregate concrete J Mat Civil Eng. 19 709-17
[19] Kazmi S M S, Munir M J, Wu Y-F, Patnaikuni I, Zhou Y and Xing F 2019 Axial stress-strain behavior of macro-synthetic fiber reinforced recycled aggregate concrete Cem Con Comp. 97 341-56
[20] Kim Y, Hanif A, Kazmi S M S, Munir M J and Park C 2018 Properties enhancement of recycled aggregate concrete through pretreatment of coarse aggregates – Comparative assessment of assorted techniques J Clean Prod. 191 339-49
[21] Ma C-K, Apandi N M, Sofrie C S Y, Ng J H, Lo W H, Awang A Z and Omar W 2017 Repair and rehabilitation of concrete structures using confinement: A review Const Build Mat. 133 502-15
[22] Mander J B, Priestley M J N and Park R 1988 Theoretical stress-strain model for confined concrete J Str Eng. 114 1804-26
[23] Mander J B, Priestley M J N and Park R 1988 Observed stress-strain behavior of confined concrete J Str Eng. 114 1827-49
[24] Xu J-J, Chen Z-P, Xiao Y, Demartino C and Wang J-H 2017 Recycled aggregate concrete in FRP-confined columns: A review of experimental results Comp Str. 174 277-91
[25] Yang Y-F and Han L-H 2006 Experimental behaviour of recycled aggregate concrete filled steel tubular columns J Const Steel Res. 62 1310-24
[26] Ahmad S H and Shah S P 1982 Stress-strain curves of concrete confined by spiral reinforcement ACI J. 79 484-90
[27] ASTM C33:2016 2016 Standard specification for concrete aggregates. In: American Society for Testing and Materials, West Conshohocken, PA
[28] Kou S-C and Poon C-S 2013 Long-term mechanical and durability properties of recycled aggregate concrete prepared with the incorporation of fly ash Cem Con Comp. 37 12-9
[29] Kou S-C, Poon C-S and Etxeberria M 2011 Influence of recycled aggregates on long term mechanical properties and pore size distribution of concrete Cem Con Comp. 33 286-91
[30] ASTM C192:2016 2016 Standard practice for making and curing concrete test specimens in the laboratory. In: American Society for Testing and Materials, West Conshohocken, PA
[31] Wu Y-F and Wei Y 2015 General stress-strain model for steel- and FRP-confined concrete Journal of Comp Const. 19 10.1061/(ASCE)CC.943-5614.0000511
[32] Xiao J, Zhang K and Akbarnezhad A 2018 Variability of stress-strain relationship for recycled aggregate concrete under uniaxial compression loading J Clean Prod. 181 753-71
[33] Kazmi S M S, Munir M J, Wu Y-F, Patnaikuni I, Zhou Y and Xing F 2019 Influence of different treatment methods on the mechanical behavior of recycled aggregate concrete: A comparative study Cem Con Comp. 104 103398
[34] Wang W, Zhang M, Tang Y, Zhang X and Ding X 2017 Behaviour of high-strength concrete columns confined by spiral reinforcement under uniaxial compression Const Build Mat. 154 496-503
[35] Teng J G, Zhao J L, Yu T, Li L J and Guo Y C 2016 Behavior of FRP-confined compound concrete containing recycled concrete lumps J Comp Const. 20 10.1061/(ASCE)CC.943-5614.0000602
[36] Pacheco J, de Brito J, Chastre C and Evangelista L 2019 Experimental investigation on the variability of the main mechanical properties of concrete produced with coarse recycled concrete aggregates *Const Build Mat.* **201** 110-20

[37] Zhao J L, Yu T and Teng J G 2015 Stress-strain behavior of FRP-confined recycled aggregate concrete *J Comp Const.* **19** 10.1061/(ASCE)CC.943-5614.0000513

[38] Carneiro J A, Lima P R L, Leite M B and Toledo Filho R D 2014 Compressive stress–strain behavior of steel fiber reinforced-recycled aggregate concrete *Cem Con Comp.* **46** 65-72

[39] Xiao J, Li J and Zhang C 2005 Mechanical properties of recycled aggregate concrete under uniaxial loading *Cem Conc Res.* **35** 1187-94

[40] Counto U J 1964 The effect of the elastic modulus of the aggregate on the elastic modulus, creep and creep recovery of concrete *Mag Conc Res.* **16** 129-38

[41] Ren X, Liu K, Li J and Gao X 2017 Compressive behavior of stirrup-confined concrete under dynamic loading *Const Build Mat.* **154** 10-22

[42] Richart F, Brandtzaeg A and Brown R 1929 The failure of plain and spirally reinforced concrete in compression. In: *Engineering Experiment Station, Bulletin no. 190,* (Urbana, USA: University of Illinois)

[43] Munir M J, Wu Y-F, Kazmi S M S, Patnaikuni I, Zhou Y and Xing F 2019 Stress-strain behavior of spirally confined recycled aggregate concrete: An approach towards sustainable design *Res, Cons Rec.* **146** 127-39
## Authors’ background

| Your Name              | Title            | Research Field | Personal website                                                                 |
|------------------------|------------------|----------------|-----------------------------------------------------------------------------------|
| Muhammad Junaid Munir  | PhD candidate    | Civil Engineering | [https://scholar.google.ca/citations?user=K8i9ntQAAAAJ&hl=en](https://scholar.google.ca/citations?user=K8i9ntQAAAAJ&hl=en) |
| Syed Minhaj Saleem Kazmi | PhD candidate | Civil Engineering | [https://scholar.google.com.pk/citations?user=riKyfDgAAA&hl=en](https://scholar.google.com.pk/citations?user=riKyfDgAAA&hl=en) |
| Yufei Wu               | Full professor   | Civil Engineering | [https://scholar.google.com/citations?user=8I0lD_UAAAAJ&hl=en&oi=sra](https://scholar.google.com/citations?user=8I0lD_UAAAAJ&hl=en&oi=sra) |
| Indubhushan Patnaikuni | Senior lecturer  | Civil Engineering | [https://scholar.google.com/citations?hl=en&user=l2kkgbYAAAAJ&view_op=list_works&sortby=pubdate](https://scholar.google.com/citations?hl=en&user=l2kkgbYAAAAJ&view_op=list_works&sortby=pubdate) |