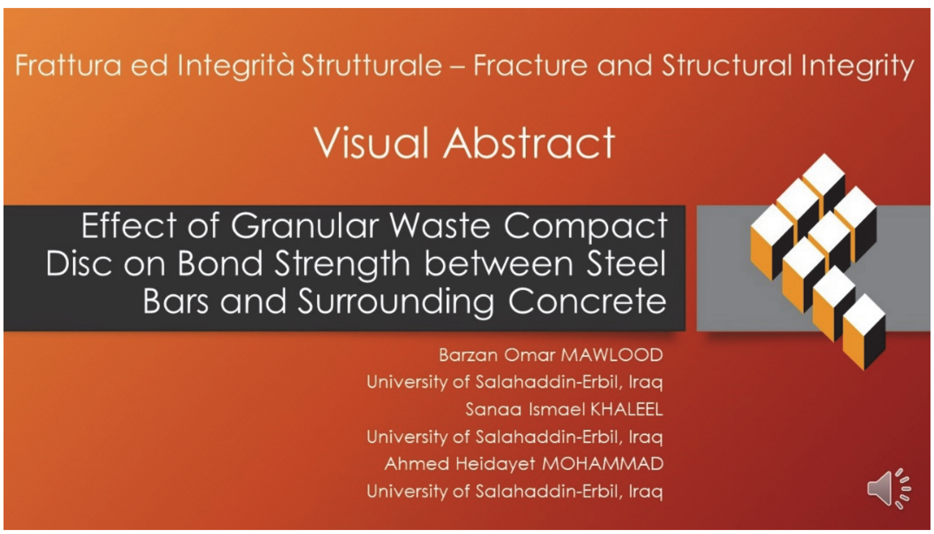
Effect of granular waste compact disc on bond strength between steel bars and surrounding concrete

Barzan Omar Mawlood, Sanaa Ismael Khaleel, Ahmed Heidayet Mohammad
University of Salahaddin-Erbil, Iraq
barzan.mawlood@su.edu.krd, https://orcid.org/0000-0002-3080-868X
sanaa.khaleal@su.edu.krd, https://orcid.org/0009-0005-3593-3681
ahmed.mohammad@su.edu.krd, https://orcid.org/0000-0003-1079-2526



OPEN ACCESS

Citation: Mawlood, B. O., Khaleel, S. I., Mohammad, A. H., Effect of granular waste compact disc on bond strength between steel bars and surrounding concrete, Frattura ed Integrità Strutturale, 67 (2024) 80-93.

Received: 27.08.2023
Accepted: 28.10.2024
Online first: 30.10.2023
Published: 01.01.2024

KEYWORDS. Bond strength, CDs waste, DVDs waste, Modified concrete.

INTRODUCTION

The universe is remarkable—as long as we do not contaminate it. The problem of electronic waste disposal, particularly that of outdated Compact discs, CDs and digital video disc, DVDs, has turned out to be serious. According to information published in 2020, more than a trillion CDs have been made since 1982, enough to orbit the Earth 30 times. Additionally, the music industry alone produced two billion CDs in 2019 [27]. The manufacture of 30 CDs per pound of plastic, according to Novak Sanitary Service [28], requires 300 cubic feet of natural gas, 2 cups of crude oil, and 24 gallons of water. Moreover, a single CD takes over 1 million years to degrade completely in a landfill. Therefore, this large number of discs can either be burned, which releases many toxic chemical gases into the air, including hydrochloric acid, sulfur dioxide, and dioxins, or used for domestic tasks or other uses. CD and DVD discs have a thickness of 1.2 mm and a weight of 20 g, and they are lacquered to prevent scratching. Aluminum and polycarbonate plastic are the materials used to make CDs and DVDs [4,28]. According to Biehn [4], these materials exhibit good flexibility and load resistance.

Researchers have concerns about the upcoming environmental problems; thus, they are working to lessen the effects and have emphasized the reuse of these discarded plastic waste in concrete ways to lessen the negative effects on the environment. According to the results of multiple studies, discarded solid waste, such as electronic waste, discarded tires, plastic, glass, steel, demolished concrete, polyethylene terephthalate plastic, and others, can be used in concrete as a partial replacement for fine aggregate. [3,5,12,16,20–24,31–33,35–37,39,42]. The results of the experiment showed that replacing a portion of the fine aggregate in concrete with shredded CDs and DVDs decreased the workability of the mix [22,37,42]. Tang et al. [37] used CD shreds in concrete to investigate the mechanical and fracture behavior of concrete using the three-point bending notched beam test. They concluded that as the size and proportion of CD shreds increased, the fracture energy and modified characteristic length increased, indicating improved brittleness and cracking resistance. According to the experimental results, the effect of the CD and DVD shred content in the concrete mixture on compressive strength is such that Tang et al. [37] have shown that compressive strength decreases with increasing disc shred content and shred size. Another result was obtained by Zainab and Jaeel [42], who noticed that the strength increased in samples containing CD and DVD shred content compared with reference samples and that the flexural and tensile strengths were improved. To recycle demolition (CD) waste, Prathab and Salini [15] used concrete aggregate waste (CAW) in the subbase layer of pavements. The results revealed that the CAW-containing mix had a higher dry density and optimum moisture content compared with other mix ratios. Mohamad et al. [25] produced lightweight mortar using CD and DVD shreds as a partial replacement for sand, and the results showed that sustainable lightweight mortar can be produced from electronic plastic trash and that it has a mechanical strength suitable for lightweight materials.

For many years, concrete has been the preferred material for construction engineering because of its availability in local areas, durability, and desirable qualities. Although concrete is a recognized brittle material, any new material (such as replacing fine aggregate with disc shards) needs more assessments and studies before being used.

For this reason, concrete is reinforced with other materials, such as iron and fiber. A reinforced concrete structure is guaranteed by the provision of an adequate bond between the reinforcing material and the concrete components. Failure of the bonds causes the structure to collapse. Therefore, it is completely established in international regulations.

The main goals of this experimental work are twofold: (1) produce environmentally friendly concrete by reusing the waste materials produced from electronic discs (CD and DVD) and (2) investigate the influence of these disc contents on the bond strength between concrete and the embedded steel bar used as reinforcement. The effect of these materials as a replacement of the partial fraction of the fine aggregate on bond strength has arguably never been the subject of a previous scientific investigation.

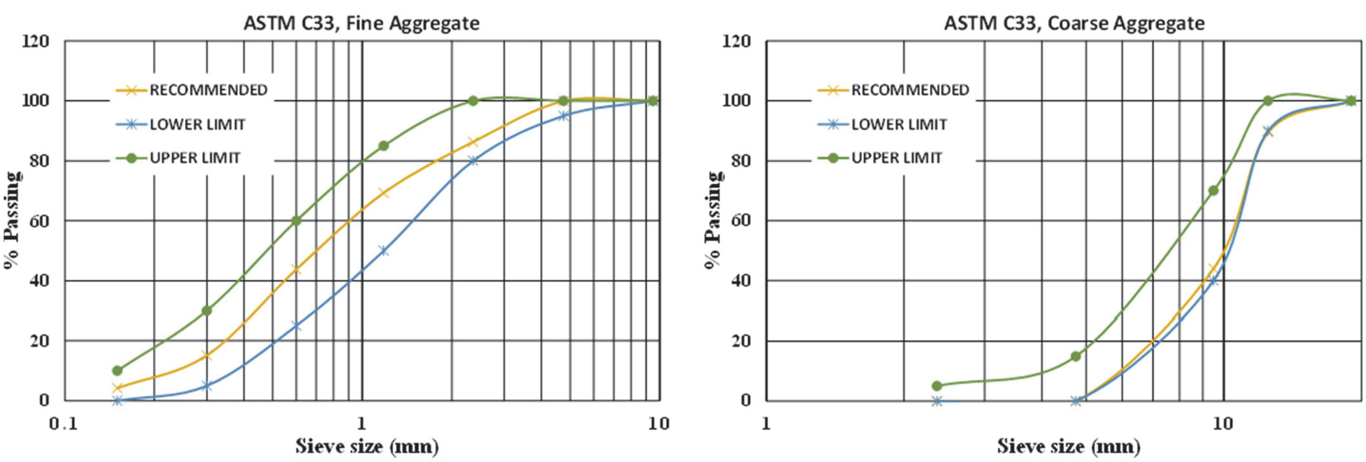


Figure 1: Particle Distribution for aggregate.

EXPERIMENTAL PROGRAM

This study investigated the bonding behavior and strength between steel bars and concrete, including waste discs (CD and DVD) as a partial fraction for fine aggregate using various percentages by weight of fine aggregate. The experimental work was conducted by pulling the steel bar embedded in a cylinder shape of concrete in accordance with ASTM C234-91A [11].

Materials

The mixture includes ordinary Portland cement (OPC) from the Mass Cement Factory – Bazyan -Kurdistan-Iraq, natural fine and coarse aggregates, and shreds of CDs and DVDs with a maximum particle size of 4.75 mm. For the aggregate, a sieve analysis test was conducted per ASTM C33 [7] to demonstrate how the particles were distributed, as illustrated in Fig. 1. Natural sand had a maximum size and fineness modulus of 2.81 and 9.5 mm, respectively. The ratio of cement:sand+disc:coarse aggregate:water was 1:2:2.5:0.4. The disc shreds were utilized to substitute partially for fine aggregate in four different weight percentages: 0%, 4%, 8%, and 12%; nevertheless, the cement-to-sand ratio was consistently 2. The CDs and DVDs that have been discarded in domestic storage facilities are the trash discs used directly for this experimental work. A Los Angeles machine initially crushed the discs into smaller size, then the final desired size was achieved using a domestic mixer (Fig. 2). Only the new fiber material sizes that were passed through a 4.75 mm sieve were accepted.

The characteristics of the average of the three steel bars of each diameter (10, 12, and 16 mm), which were inserted into a concrete cylinder, are shown in Tab. 1.

Bar diameter (mm)		Load (KN)		Stress (MPa)		Elongation %
Nominal	Actual	Yield	Ultimate	Yield	Ultimate	
10	9.70	27.55	40.96	373	554	24.00
12	11.37	49.36	62.13	486	612	18.00
16	15.80	113.80	137.73	581	703	15.00

Table 1: Mechanical property of reinforced bars.

Figure 2: Disc shredding procedures: (a) Disc collection, (b) Crushing discs by Los Angeles machine, (c) Disc particle sizes after Los Angeles machine, and (d) A domestic mixer and sieving to produce the desired particle size.

Specimens

The ingredients were mixed using a rotary mixer based on the mix proportion. The pull-out test was conducted using a concrete cylinder shape (diameter: 150 mm) that was cast in a laboratory at ambient temperature. The deformed bars were initially positioned in the center of a 10 mm wooden circular piece fixed at a specified height inside the molds (cylinders). Approximately 600 mm of the steel bar had to be cut away from the concrete for it to fit into the grip of the tensile testing machine. The molds were first filled with three layers of concrete, compacted using an electric concrete vibrating table, and leveled on the top face of the concrete cylinders. Then, the specimens were left at room temperature for 24 hours before being demolded and finally put away to cure for 28 days in a water tank. Simultaneously, control specimens, which consisted of (100 × 200) mm cylinders, and (75 × 75 × 370) mm prisms were cast to follow the characteristics of the mix, which included the compressive, tensile, and flexural strengths of concrete. Fig. 3 provides an illustration of the previously described statements.

Figure 3: Casting the specimens: (a) Weighing the ingredients and mixing with mixer, (b) Positioning and fixing the steel bars with circular piece of wood inside the molds, (c) Putting the molds on the vibrating table, and (d) Casting and storing the specimens at ambient temperature.

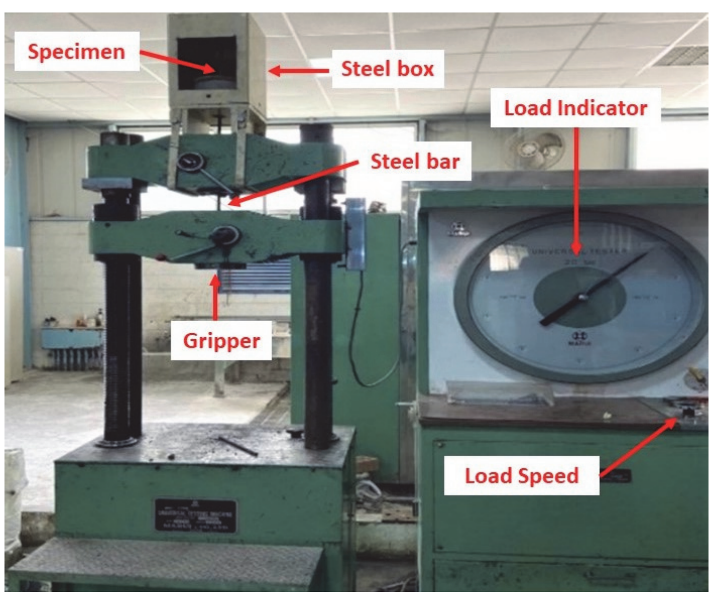


Figure 4: Pull-out test specimens set up on universal testing machine.

Conducting tests

In this study, the influence of CD and DVD shreds as a partial replacement of sand on the characteristics of concrete was studied. The three control specimens were cast simultaneously for each mix proportion and tested in accordance with the ASTM specification for compressive [8], splitting tensile strength [10], and flexural strength testing [9]. The pull-out test was conducted on the 36 cylindrical concrete shapes arranged in four groups, complying with the recommendations of ACI 408R-03 [2]. The embedded lengths for each of the three bar sizes, i.e., 10, 12, and 16 mm, are 50, 100, and 150 mm, respectively (Tab. 2). The specimens' designation in Tab. 2 is as follows: D0-1 designates the specimen with a zero percentage of disc material, which is number one.

The bar was pulled by a uniaxial tension force of up to 1000 kN at a rate of approximately 0.3 kN per second until it yielded, fractured, or developed a crack in the concrete. To set up and conduct the tests, Fig. 4 demonstrates how to install a steel box plate on the cylinder cap and set the samples in a universal test machine upside down.

Mix No.	Specimen No.	Disc Content (%)	Bar Diameter, d_b (mm)	Embedded Length, l_d (mm)
	D0-1			50
	D0-2		10	100
	D0-3			150
	D0-4			50
M1	D0-5	0	12	100
	D0-6			150
	D0-7			50
	D0-8		16	100
	D0-9			150
	D4-10			50
	D4-11		10	100
	D4-12			150
	D4-13			50
M2	D4-14	4	12	100
	D4-15			150
	D4-16			50
	D4-17		16	100
	D4-18			150
	D8-19			50
	D8-20		10	100
	D8-21			150
	D8-22			50
M3	D8-23	8	12	100
	D8-24			150
	D8-25			50
	D8-26		16	100
	D8-27			150
	D12-28			50
	D12-29		10	100
	D12-30			150
	D12-31			50
M4	D12-32	12	12	100
	D12-33			150
	D12-34			50
	D12-35		16	100
	D12-36			150

Table 2: Pull-out specimens' designation.

RESULTS AND DISCUSSION

Concrete Strengths

The mechanical properties of the concrete mixtures, including the compressive strength based on cylinders (100 mm × 200 mm), splitting tensile strength of cylinders (100 mm × 200 mm), and flexural strength of prisms (75 mm × 75 mm × 380 mm), were experimentally tested and are shown in Tab. 3.

	Mix No.	M1	M2	M3	M4
	Disc Content (%)	0	4	8	12
Average cylinder compressive strength	(MPa)	31.7	35.3	24.9	24.5
Standard Deviation, SD	(MPa)	7.28	2.75	4.53	2.19
Coefficient of Variance, CV	(%)	22.96	7.79	18.19	8.94
Average cylinder splitting strength	(MPa)	3.2	3.6	3.3	2.9
Standard Deviation, SD	(MPa)	1.25	0.58	0.17	0.3
Coefficient of Variance, CV	(%)	39.06	16.11	5.15	10.34
Prism flexural strength (MPa)	(MPa)	4.5	5.8	4.3	4.8
Standard Deviation, SD	(MPa)	3.33	0.10	3.08	0.15
Coefficient of Variance, CV	(%)	74.00	1.72	71.62	3.12

Table 3: Mechanical property of concrete mixtures.

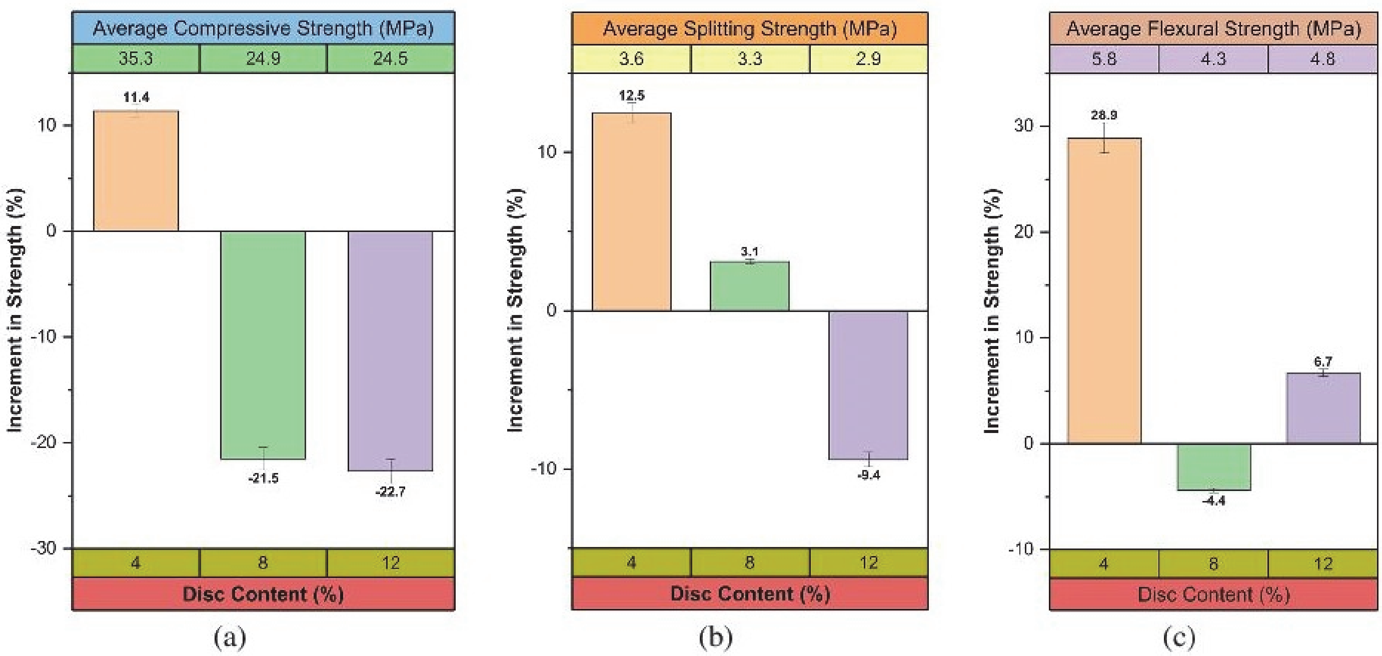


Figure 5: Effect of disc waste on mechanical properties of concrete: (a) Compressive strength, (b) Splitting strength, and (c) Flexural strength.

The average compressive strength resulted from three cylinders that were simultaneously cast for each mix design. The effect of disc content on compressive strength varied depending on the percentage of disc content (Fig. 5a), but overall, a considerable improvement in compressive strengths can be seen for M2 (4% of disc content). However, the strength increased by 11.4% at the 4%-disc content, which was optimal for the cylinder shape; thereafter, the strength decreased with sand replacement reaching 8% and 12%, and the amount of decrease reached 21.5% and 22.7%, respectively. A similar result was obtained by Zainab and Jaeel [42] who observed that the compressive strength increased by increasing the waste disc content as a partial amount of fine aggregate up to a specified amount of waste disc content. Given that discs are an insoluble substance with a low ability to absorb water and low hardness, the low bond force on the fine aggregate with surrounding concrete may have caused the decrease in concrete strength resulting from adding more disc to the mix. However, the average strength is higher than the minimum compressive strength (i.e., 17 MPa) specified in the ACI 318-19 code [1] for structural concrete.

The results of the experiment revealed the disc waste could improve the tensile strength of concrete in the splitting tensile and flexural test results at a lower percentage of sand replacement. The increments were considerably less than those observed in compressive strength and complied with the results obtained by [37,38]. The average tensile strengths of the modified concrete determined by the splitting tensile strength test method improved by 12.5% and 3.1% when the percentage of disc content was increased from 0% to 4% and 8%, respectively, but reduced by 9.4% as the percentage of disc content was increased to 12%. The situation had the opposite influence on the specimens' flexural strength; as the disc contents increased, the effect flipped. In other words, at 4% disc content, the flexural strength improved by 26.9%; at 8% disc content, it decreased by 4.4%; and at 12% disc content, it increased by 6.7%. However, the conclusions derived from the experimental data tests are not reasonable.

Mix No.	Specimen No.	Disc Content (%)	d_b (mm)	l_d (mm)	P (kN)	U (MPa)	Failure Shape
M1	D0-1	0	10	50	10.69	7.02	Splitting-2 pieces
	D0-2			100	33.65	11.04	Splitting-2 pieces
	D0-3			150	41.2	-----	Yield and Fracture
	D0-4		12	50	18.34	10.27	Splitting-2 pieces
	D0-5			100	28.15	7.88	Splitting-2 pieces
	D0-6			150	65.73	-----	Yield and Fracture
	D0-7		16	50	10.1	4.07	Splitting-2 pieces
	D0-8			100	32.77	6.60	Splitting-2 pieces
	D0-9			150	64.55	8.67	Splitting-2 pieces
M2	D4-10	4	10	50	13.15	8.63	Splitting-3 pieces
	D4-11			100	41.59	-----	Yield and Fracture
	D4-12			150	40.81	-----	Yield and Fracture
	D4-13		12	50	21.09	11.81	Splitting-3 pieces
	D4-14			100	32.37	9.06	Splitting-3 pieces
	D4-15			150	62.2	-----	Yield and Fracture
	D4-16		16	50	12.36	4.98	Splitting-3 pieces
	D4-17			100	39.04	7.87	Splitting-2 pieces
	D4-18			150	76.91	10.33	Splitting-3 pieces
M3	D8-19	8	10	50	9.42	6.18	Splitting-3 pieces
	D8-20			100	32.96	10.82	Splitting-2 pieces
	D8-21			150	41.45	-----	Yield and Fracture
	D8-22		12	50	10.99	6.15	Splitting-2 pieces
	D8-23			100	49.15	13.76	Splitting-2 pieces
	D8-24			150	53.42	-----	Yield and Fracture
	D8-25		16	50	19.57	7.89	Splitting-3 pieces
	D8-26			100	41.01	8.26	Splitting-3 pieces
	D8-27			150	76.13	10.22	Splitting-3 pieces
M4	D12-28	12	10	50	11.77	7.72	Splitting-2 pieces
	D12-29			100	39.24	12.88	Splitting-2 pieces
	D12-30			150	42.43	-----	Yield and Fracture
	D12-31		12	50	5.79	3.24	Slip
	D12-32			100	32.72	9.16	Splitting-3 pieces
	D12-33			150	48.07	8.97	Splitting-2 pieces
	D12-34		16	50	22.17	8.93	Splitting-2 pieces
	D12-35			100	24.13	4.86	Splitting-2 pieces
	D12-36			150	83.97	11.28	Splitting-4 pieces

Table 4: Pull-out test results.

Bond Strengths

The norm for the construction of a secure or reliable reinforced concrete structure is the strength of the bond developed between the constituent concrete particles and the steel bar through which it is extended. When exposed to an external

force, many parameters that control the bond strength completely coincide. Key factors that have an immediate effect on the bond strength between the components during usage include the embedded length or anchorage length of the steel bar, the hardness and shape of the bar surface, the bar diameter, the strength of the concrete, and the mix composition.
The following basic equation used to compute the bond strength U, which depends on the applied load required to pull-out the bar until failure P in kN, the length l_b, and diameter d_b of the embedded steel bar in mm:

$$U = \frac{P}{\pi d_b l_b} \tag{1}$$

Tab. 4 shows the experimental load based on the specimens' pull-out test results and the bond strength estimated using Eqn. 1 with the specimens' failure mode. During the test, three distinct modes of failure were observed: the steel bar yielded and then ruptured, indicating the presence of a suitable bond; the steel bar slipped from the surrounding concrete of the specimen; or the concrete cracked into multiple pieces.

10 mm-diameter Steel Bar

Compared with reference specimen D0-1, the bond strength at 4% and 12% of disc content for 50 mm of embedded length increased by 22.5% and 10% for specimens D4-10 and D12-28, respectively, as indicated in Tab. 4 and Fig. 6. The bond strength increased as the disc content increased when the anchorage length was increased to 100 mm, and the perfect bond was attained at 4% of the disc content by yielding the bar before fracture. The failure bond caused the steel bar to yield and fracture, demonstrating that a perfect bond exists between the concrete and the embedded bar. This type of failure is preferred by site engineers. The embedded length at 150 mm obtained the best bond between the steel bars and the surrounding concrete because all failures were the yield and rapture of the steel. This result means that the full potential energy is absorbed from the steel bars.
In general, the addition of discs to concrete can improve the bond strength between the bar and the surrounding concrete and can reduce the length of anchorage needed.

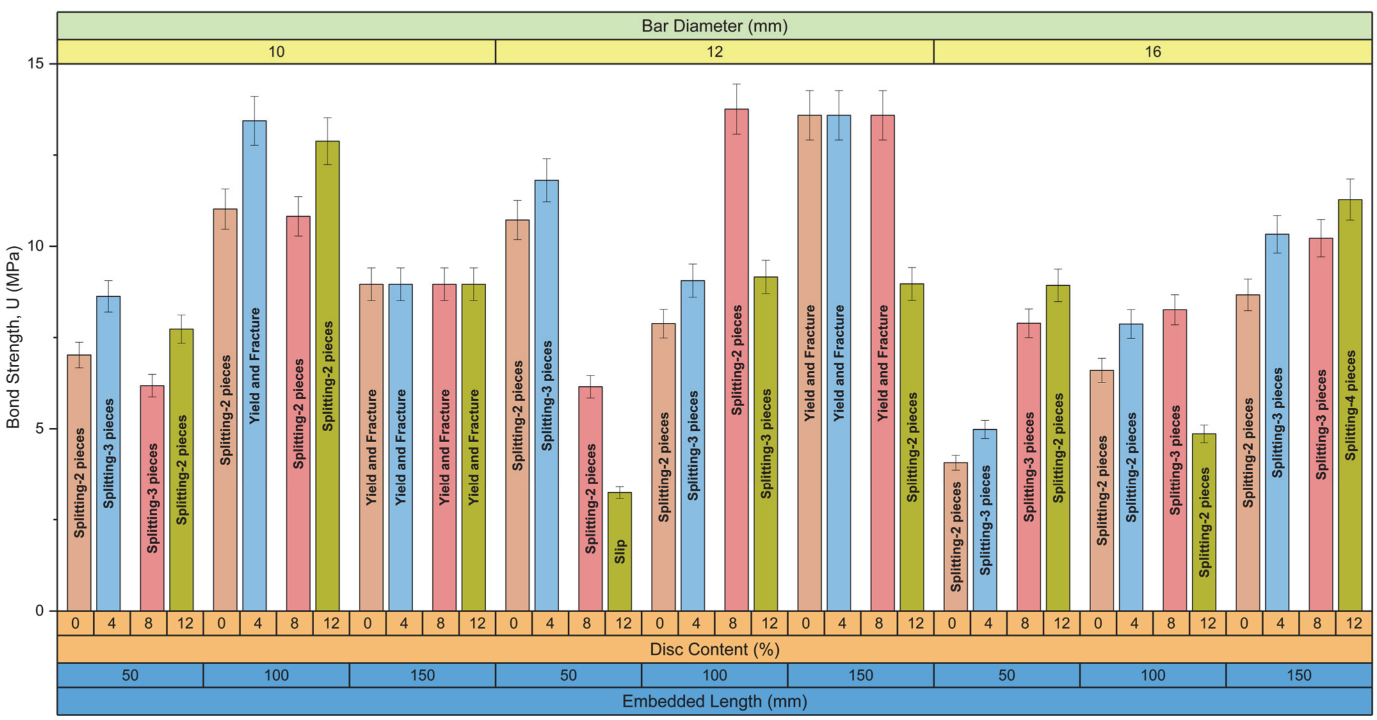


Figure 6: Particle Distribution for aggregate.

12 mm-diameter Steel Bar

The bond strength was also enhanced for 50 mm embedded length as the disc content increased from 0% to 4% by an amount of 10.2% at specimen D4-13, followed by a decrease as the disc increased to 8% by 42.6%, as shown in Tab. 4. A slippage of the bar occurred for specimen D12-31 when the disc content increased to 12%, whereas the pull-out load was 5.79 kN at a lower fiber content. This result indicates that the thin concrete (i.e., 50 mm development length) caused the steel bar to be pulled out of the concrete, which was also reflected in the specimen's splitting tensile strength reaching 2.9 MPa. The bond strength was also improved when the disc content reached up to 8% by 74.6% at specimen D8-23 as the embedded length amounted to 100 mm, but it decreased when it did so to 12%. For a length of 150 mm, the bond developed sufficiently, but in specimen D12-33, the opposite behavior was exhibited probably because of how the disc shreds spread during concrete casting, which resulted in inhomogeneous concrete; thus, weakness occurs at a high percentage of fiber content (12%).

16 mm-diameter Steel Bar

Fig. 6 depicts how the disc content affected the bonding strength for a bar with a 16 mm diameter. In general, the bond strength increased as the disc content increased, as shown in Fig 6. The greatest bond strength was reached at 12%, 8%, and 12% of the disc content for embedded lengths of 50, 100, and 150 mm, respectively. The increments were 119.4%, 25.2%, and 30.1% at specimens D4-18, D8-26, and D12-36, respectively.

Failure Mode

The specimens failed in one of the following manners during the test: either the concrete split into two, three, or four pieces; the steel bar slipped through the concrete without developing cracks; or the steel bar succumbed before fracturing. The preferred failure is the yielding of the steel bar, and the reinforced concrete is designed on the basis of this idea.

Except for the D12-31 specimen, all the specimens in this work failed either by concrete cracking or yielding of the steel bar. For the 10 mm-diameter steel bars, the surrounding concrete cracked without being much affected by the disc content, and as demonstrated in Fig. 7, the failure was the splitting of the concrete into two and three pieces as the disc contents changed from 0% to 4%, 8%, and 12% for the embedded length up to 100 mm. However, when the steel bar diameter was increased to 12 and 16 mm, the same failure shapes were observed, with the exception of specimen D12-31, which had a steel bar (diameter: 12 mm) embedded 50 mm into concrete with a disc content of 4%. In this case, the failure was due to bar slipping.

Figure 7: Failure modes of pull-out specimens.

COMPARISON WITH ACI CODE

The minimal development length needed to be embedded in concrete is determined by applying the ACI-318's approved equation [1] based on the steel's yield strength f_y, the concrete cylinder's compressive strength $f_c^{'}$, the diameter of the bar d_b, and the concrete cover c_b. The following equation l_d determines the development length:

$$l_d = \left(\frac{f_y}{1.1\lambda\sqrt{f_c^{'}}} \right) \left(\frac{\psi_l \ \psi_s \ \psi_e \ \psi_g}{\left(\frac{c_b + k_{tr}}{d_b} \right)} \right) d_b \qquad 2)$$

were the restriction of ACI-318 Code $\frac{c_b + k_{tr}}{d_b} \leq 2.5$, is not taken into consideration in this case. The additional variables include (ψ_l , ψ_s, ψ_e, and ψ_g) that pertain to reinforcement, such as position, size, epoxy coating, and grade, respectively. The values adopted were $\psi_l = 1$ for non-top reinforcement, $\psi_s = 0.8$ for $d_b < 19\ mm$, $\psi_e = 1.0$ for uncoated bars, and $\psi_g = 1.0$ for steel grade $f_y \leq 420\ MPa$ and $\psi_g = 1.15$ for $f_y = 550\ MPa$.

The experimental data show that only specimens D0-3, D0-6, D4-11, D4-12, D4-15, D8-12, D8-24, and D12-30 have the required embedding length at 150 mm, except D4-11 at 100 mm, due to the failure of steel bar fracture. When the minimum development length according to the ACI code was determined using Eqn. 2, the calculated and experimental lengths differed noticeably; for instance, for specimen D8-24, the minimum development length determined using Eqn. 2 was 977 mm, which was nearly 552% longer than the adequate development length of 150 mm needed to fracture the steel bar experimentally.

Mawlood et al. [30] attempted to determine the concrete type factor λ for geopolymer concrete by equating Eqn. 1 to the tensile force of the steel bar to obtain the development length, as written in Eqn. 3. Then, l_d is substituted in Eqn. 2 to obtain λ as shown below:

$$l_d = \left(\frac{d}{4} \right) \left(\frac{f_y}{f_b} \right) \qquad 3)$$

$$\lambda = \left(\frac{f_y}{1.1\ l_d\sqrt{f_c^{'}}} \right) \left(\frac{\psi_l \ \psi_s \ \psi_e \ \psi_g}{\left(\frac{c_b + k_{tr}}{d_b} \right)} \right) d_b \qquad (4)$$

where l_d is the development length, d is bar diameter, and f_b is the experimental bond strength. On the basis of the data from this work and 136 test data points from 24 pull-out cylindrical shape test data by Albarwary and Haido [6], 6 pull-out cubic shape test data by Bilek et al. [13], 12 pull-out cubic concrete specimen data by Carvalho et al. [14], 6 pull-out cubic shape test data by Chu and Kwan [17], 4 pull-out cubic shape test data by Ganesan et al. [18], 16 pull-out cubic shape test data by Garcia-Taengua et al. [19], 4 pull-out cylindrical shape test by Mohammad et al.[26], 4 pull-out cubic shape test data by Nuroji et al. [29], 24 pull-out prism shape test data by Sarker [34], 16 pull-out cubic shape test data by Yalciner et al. [40], and 20 pull-out cubic shape test data by Yang et al.[41], the same approach was repeated. As shown in Fig. 8, the plotted data were fitted using Origin Pro, and a logarithmic equation was statistically found to estimate the value of λ, which is dependent on the bond strength concrete compressive strength and increases as the bond strength increases.

$$\lambda = a - b\ln\left(\frac{f_b}{\sqrt{f_c^{'}}} + c\right) \tag{5}$$

The empirical constants a, b, and c can be estimated as −13.702, −14.783, and 2.216, respectively, for the fitted equation, with statistical analysis providing reduced chi-square, R-square (COD), and adj. R-square of 0.8599, 0.8983, and 0.8971, respectively. By using Eqn. 4 and substituting the experimental mean strength, λ can be estimated as 6.750 and 7.954 for normal concrete and concrete including disc waste, respectively. Despite the fact that Eqn. 2's λ value for normal concrete is 1 in compliance with ACI code requirements, the factor was normalized by dividing 6.750 to obtain a new λ value that is 1.2 for concrete with disc content.

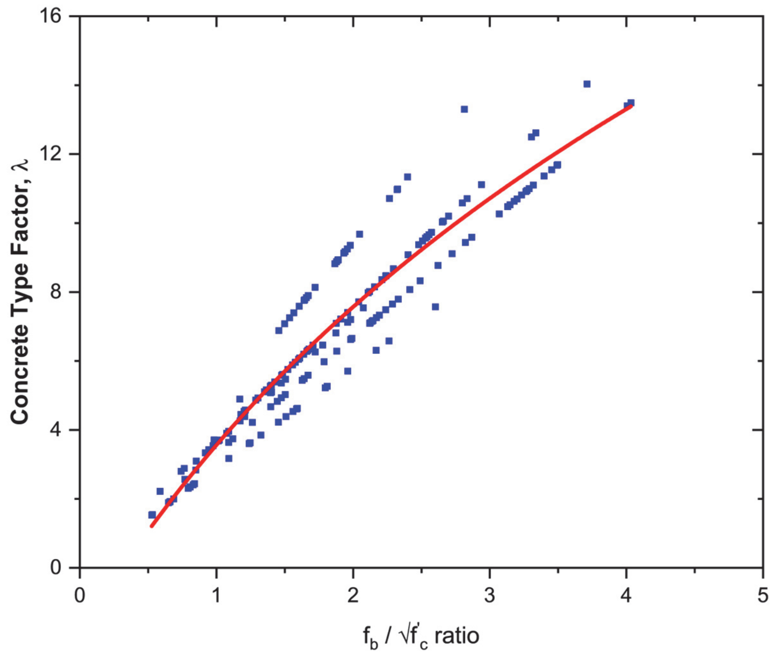


Figure 8: Data fit equation in concrete type factor determination.

Conclusions

The results gathered from 36 pull-out test specimens on cylindrical concrete were used to examine how the behavior of the bond strength between the steel bar and the surrounding concrete was affected by the behavior of disc waste shreds (CDs and DVDs) led to the following conclusions:

1. In general, at a specific disc content of approximately 4%, replacing a portion of the fine aggregate in concrete with waste CD and DVD shreds improves the mechanical properties of the concrete. The improvements in compressive strength, splitting tensile strength, and flexural strength reach 11.4%, 12.5%, and 28.9%, respectively.
2. The average compressive strength is more than the minimum allowable compressive strength specified in the ACI code for structural concrete (i.e., 17 MPa).
3. Concrete that contains discs splits into more fragments than typical concrete. This result indicates that the load was effectively distributed from the steel bar to the surrounding material.
4. For a bar diameter of 10 mm, the bond strength is improved as the embedded length increases for all mix groups; the perfect bond strength is achieved in all specimens at 150 mm embedded length, except for specimen D4-11, which had 4% of the disc contained at 100 mm embedded length.
5. However, for a bar diameter of 12 mm, the bond strength decreases as the embedded length increases for specimens of the M1 (specimens D0-1–D0-9, which had 0% disc content) and M2 (specimens D4-10–D4-18, which had 4% disc content) groups, but the effect is reversed for specimens of the M3 (specimens D8-19–D8-27, which had 8% disc content) and M4 groups (specimens D12-28–D12-36, which had 12% disc content); the perfect bond strength is

attained in all specimens at a 150 mm embedded length, except for specimens of the M4 group (specimens D12-28–D12-36, which had 12% disc content).

6. However, relative to a bar diameter of 16 mm, the bond strength is also improved due to an increase in the development length, and the failure mechanism is caused by the surrounding concrete splitting into several pieces.
7. To make the computation of the minimum development length used by the ACI code equation more reliable and reasonable, a new concrete factor was statistically estimated for this type of concrete in this work.

Acknowledgments

The authors would like to express their gratitude to the efforts of Asia M. A., Sozan J. S., Rayan G. M., Soryaz H. A., Khanda Q. O., Sana T. A., Zahraa S. S., Bushra A. A., Ali L. F., Limo H. M. and Rawand J. H., and Hazhan O. M. in the experimental work and the technical staff and laboratory of the civil engineering department.

References

[1] ACI Committee 318. (2019). ACI CODE-318-19: Building Code Requirements for Structural Concrete and Commentary, Farmington Hills, American Concrete Institute.
[2] ACI Committee 408. (2003). 408R-03: Bond and Development of Straight Reinforcing Bars in Tension, pp. 1–49.
[3] Akçaözoğlu, S., Atiş, C.D., Akçaözoğlu, K. (2010). An investigation on the use of shredded waste PET bottles as aggregate in lightweight concrete, Waste Management, 30(2), pp. 285–290. DOI: 10.1016/j.wasman.2009.09.033.
[4] Alan W. Biehn. (2008). Compact Discard: Finding Environmentally Responsible Ways to Manage Discarded Household CDs and DVDs. University of Pennsylvania.
[5] Albano, C., Camacho, N., Hernández, M., Matheus, A., Gutiérrez, A. (2009). Influence of content and particle size of waste pet bottles on concrete behavior at different w/c ratios, Waste Management, 29(10), pp. 2707–2716. DOI: 10.1016/j.wasman.2009.05.007.
[6] Albarwary, I.H.M., Haido, J.H. (2013). Bond Strength of Concrete with The Reinforcement Bars Polluted with Oil, European Scientific Journal, ESJ, 9(6). DOI: 10.19044/esj.2013.v9n6p%p.
[7] ASTM C33/C33M-18. (2018). Standard Specification for Concrete Aggregates, vol. 04.02, West Conshohocken, ASTM International, DOI: 10.1520/C0033_C0033M-18.
[8] ASTM C39/C39M-21. (2021). Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, vol. 04.02, West Conshohocken, ASTM International, DOI: 10.1520/C0039_C0039M-21.
[9] ASTM C78/C78M-22. (2022). Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading), vol. 04.02, West Conshohocken, ASTM International, DOI: 10.1520/C0078_C0078M-22.
[10] ASTM C496/C496M-17. (2017). Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, vol. 04.02, West Conshohocken, ASTM International, DOI: 10.1520/C0496_C0496M-17.
[11] ASTM-C234. (1991). Standard Test Method for Comparing Concretes on the Basis of the Bond Developed with Reinforcing Steel, West Conshohocken, ASTM International.
[12] Batayneh, M., Marie, I., Asi, I. (2007). Use of selected waste materials in concrete mixes, Waste Management, 27(12), pp. 1870–1876. DOI: 10.1016/j.wasman.2006.07.026.
[13] Bilek, V., Bonczková, S., Hurta, J., Pytlík, D., Mrovec, M. (2017). Bond Strength Between Reinforcing Steel and Different Types of Concrete, Procedia Engineering, 190, pp. 243–247. DOI: 10.1016/j.proeng.2017.05.333.
[14] Carvalho, E.P., Ferreira, E.G., Cunha, J.C. da., Rodrigues, C. de S., Maia, N. da S. (2017). Experimental Investigation of Steel-Concrete Bond for Thin Reinforcing Bars, Latin American Journal of Solids and Structures, 14(11), pp. 1932–1951. DOI: 10.1590/1679-78254116.
[15] Chandra Prathap, R., Salini, U. (2022). Experimental Investigation on the Feasibility of Using Construction Demolition Waste Materials for Subbase Layer in Flexible Pavement, Proceedings of the Fifth International Conference of Transportation Research Group of India, Lecture Notes in Civil Engineering, 218, pp. 193–200. DOI: 10.1007/978-981-16-9921-4_13.
[16] Choi, Y.-W., Moon, D.-J., Chung, J.-S., Cho, S.-K. (2005). Effects of waste PET bottles aggregate on the properties of concrete, Cement and Concrete Research, 35(4), pp. 776–781. DOI: 10.1016/j.cemconres.2004.05.014.
[17] Chu, S.H., Kwan, A.K.H. (2018). A new method for pull out test of reinforcing bars in plain and fibre reinforced concrete, Engineering Structures, 164, pp. 82–91. DOI: 10.1016/j.engstruct.2018.02.080.

[18] Ganesan, N., Indira, P.V., Sabeena, M.V. (2014). Bond stress slip response of bars embedded in hybrid fibre reinforced high performance concrete, Construction and Building Materials, 50, pp. 108–115. DOI: 10.1016/j.conbuildmat.2013.09.032.
[19] Garcia-Taengua, E., Martí-Vargas, J.R., Serna, P. (2016). Bond of reinforcing bars to steel fiber reinforced concrete, Construction and Building Materials, 105, pp. 275–284. DOI: 10.1016/j.conbuildmat.2015.12.044.
[20] Hama, S.M., Hilal, N.N. (2017). Fresh properties of self-compacting concrete with plastic waste as partial replacement of sand, International Journal of Sustainable Built Environment, 6(2), pp. 299–308. DOI: 10.1016/j.ijsbe.2017.01.001.
[21] Hannawi, K., Prince, W., Kamali-Bernard, S. (2010). Effect of Thermoplastic Aggregates Incorporation on Physical, Mechanical and Transfer Behaviour of Cementitious Materials, Waste Biomass Valorization, 1(2), pp. 251–259. DOI: 10.1007/s12649-010-9021-y.
[22] Himanshu Rane., Puneet Patel., Prajakta Adate., Saurabh Jadhav., Namrata Patil., Prof. Viraj Kashikar. (2018). Environment Friendly Concrete by Replacement of Coarse Aggregates by waste CD's, International Journal of Engineering Research & Technology, 7(7), pp. 397–399. DOI: 10.17577/IJERTV7IS040366.
[23] Hossain, M., Bhowmik, P., Shaad, K. (2016). Use of waste plastic aggregation in concrete as a constituent material, Progressive Agriculture, 27(3), pp. 383–391. DOI: 10.3329/pa.v27i3.30835.
[24] Marzouk, O.Y., Dheilly, R.M., Queneudec, M. (2007). Valorization of post-consumer waste plastic in cementitious concrete composites, Waste Management, 27(2), pp. 310–318. DOI: 10.1016/j.wasman.2006.03.012.
[25] Mohamad, S.A., Zuhaira, A.A., Al-Hamd, R.Kh.S., Alzabeebee, S. (2023). The production of novel sustainable lightweight mortar from the electronic plastic waste, Materials Today: Proceedings. DOI: 10.1016/j.matpr.2023.02.336.
[26] Mohammad, A.H., Abdulrazzaq, N.M., Mawlood, B.O. (2019). Bond between Steel Bar Embedded in High Strength Self Compacting Concrete with and without Fibers., 2019 International Engineering Conference (IEC), IEEE, pp. 227–232.
[27] Nimble. (2020). Compact Discs: An Untapped Resource.
[28] Novak Sanitary Service. (2021). Reduce E-Waste by Following This CD/DVD Recycling Guide.
[29] Nuroji, Herdian Primadyas, D., Nurhuda, I., Muslikh. (2018). The Comparison of Bond Strength between Geopolymer Concrete and OPC Concrete for Plain Reinforcing Bars, MATEC Web of Conferences, 159, p. 01017. DOI: 10.1051/matecconf/201815901017.
[30] Omar, M.B., Heidayet, M.A., Khidhir, B.D. (2022). Bond strength of deformed steel bars embedded in geopolymer concrete, Advances in Concrete Construction, 14(5), pp. 331–339. DOI: 10.12989/ACC.2022.14.5.331.
[31] Panyakapo, P., Panyakapo, M. (2008). Reuse of thermosetting plastic waste for lightweight concrete, Waste Management, 28(9), pp. 1581–1588. DOI: 10.1016/j.wasman.2007.08.006.
[32] Pedreño-Rojas, M.A., Morales-Conde, M.J., Pérez-Gálvez, F., Rubio-de-Hita, P. (2020). Reuse of CD and DVD Wastes as Reinforcement in Gypsum Plaster Plates, Materials, 13(4), p. 989. DOI: 10.3390/ma13040989.
[33] Rebeiz, K.S. (1995). Time-temperature properties of polymer concrete using recycled PET, Cement and Concrete Composites, 17(2), pp. 119–124. DOI: 10.1016/0958-9465(94)00004-I.
[34] Sarker, P.K. (2011). Bond strength of reinforcing steel embedded in fly ash-based geopolymer concrete, Materials and Structures, 44(5), pp. 1021–1030. DOI: 10.1617/s11527-010-9683-8.
[35] Siddique, R., Khatib, J., Kaur, I. (2008). Use of recycled plastic in concrete: A review, Waste Management, 28(10), pp. 1835–1852. DOI: 10.1016/j.wasman.2007.09.011.
[36] Silva, D.A., Betioli, A.M., Gleize, P.J.P., Roman, H.R., Gómez, L.A., Ribeiro, J.L.D. (2005). Degradation of recycled PET fibers in Portland cement-based materials, Cement and Concrete Research, 35(9), pp. 1741–1746. DOI: 10.1016/j.cemconres.2004.10.040.
[37] Tang, W.C., Lo, Y., Cui, H.Z. (2011). Size Effect of Waste Compact Disc Shred on Properties of Concrete, Advanced Materials Research, 346, pp. 40–46. DOI: 10.4028/www.scientific.net/AMR.346.40.
[38] Tang, W.C., Ng, K.M., Lo, T.Y., Tam, C.M. (2008). Fracture properties of concrete with waste compact disc shred, Materials Research Innovations, 12(4), pp. 179–183. DOI: 10.1179/143307508X362819.
[39] Tawfik, M.E., Eskander, S.B. (2006). Polymer Concrete from Marble Wastes and Recycled Poly(ethylene terephthalate), Journal of Elastomers & Plastics, 38(1), pp. 65–79. DOI: 10.1177/0095244306055569.
[40] Yalciner, H., Eren, O., Sensoy, S. (2012). An experimental study on the bond strength between reinforcement bars and concrete as a function of concrete cover, strength and corrosion level, Cement and Concrete Research, 42(5), pp. 643–655. DOI: 10.1016/j.cemconres.2012.01.003.
[41] Yang, H., Lan, W., Qin, Y., Wang, J. (2016). Evaluation of bond performance between deformed bars and recycled aggregate concrete after high temperatures exposure, Construction and Building Materials, 112, pp. 885–891. DOI: 10.1016/j.conbuildmat.2016.02.220.

[42] Zainab Z. Ismail., Ali J. Jaeel. (2016). Environmental Friendly Concrete Using Waste Compact Discs as Fine Aggregate Replacement., In: Peter Claisse, Esmaiel Ganjian, Tarun Naik eds., Fourth International Conference on Sustainable Construction Materials and Technologies, Las Vegas, Coventry University.